A SURVEY AND ENGINEERING DESIGN OF ATMOSPHERIC DIVING SUITS

A REPORT

by

MICHAEL ALBERT THORNTON

SUBMITTED TO DR. ROBERT RANDALL

Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING

December 2000

Major Subject: Ocean Engineering

ABSTRACT

A Survey and Engineering Design of

Atmospheric Diving Suits (December 2000)

Michael Albert Thornton, Bachelor of Mechanical Engineering, Auburn University

Chair of Advisory Committee: Dr. Robert E. Randall

The objective of this report is to describe the results of a worldwide industry survey of the atmospheric diving suit (ADS). A glimpse into the past of significant ADSs from Lethbridge's 1715 "diving engine" to the well-recognized JIM suit is discussed. Several facets are presented concerning present day ADSs, including a closer look at the ADSs in operation today in the offshore oil and gas industry and in the deep submergence programs of several international navies. A comparison of current ADSs against other available means of underwater intervention is made that demonstrates the advantages and disadvantages of each. A general discussion of the engineering factors to be considered in the design and construction of ADSs is presented as well. Based on direct interviews with executives, technicians and operators directly involved, insight is gained into the future of ADSs, including the latest and forthcoming suits such as, the HARDSUIT 2000 - the U.S. Navy's latest submarine rescue tool, Oceaneering's WASP renovation - of which two are expected be in operation by early 2001, and the futuristic but plausible EXOSUIT, the latest prototype shallow-water swimmable ADS. The results of this survey indicate that atmospheric diving suits are a healthy and thriving community among the oil and gas industry, yet comfortable in their niche between the ambient divers and remotely operated vehicles.

DEDICATION

This report is dedicated to my wife, Melda Elaine Thornton, without whose support I could never have completed a this task, and my two miracle children, Michael Hebreux, 7/7/97, and Isaac James, 1/1/2000, who endured countless days in which their father was absent working on this project.

and to

Jay Shapcotte, 10/10/58 - 08/29/99, who was a keen advocate of Atmospheric diving suits and had an association with them for nearly 20 years. Beginning his career as a wet diver, Jay shifted to the atmospheric diving community in 1980. He began diving the JIM suit and switched to the WASP suit as the JIM suit was phased out. Jay accumulated many thousands of hours in atmospheric diving suits, especially the WASP, and was a respected and integral part of a closely knit group of highly trained individuals. Not only his sense of humor and personality but his expertise will be missed by everyone he touched or came in contact with. Jay died doing what he loved most, solving problems in a hostile offshore environment, diving a suit he grew to love so much. Jay left behind a wife Tracy, a daughter Courtney, and a son Miles.

ACKNOWLEDGEMENTS

Special acknowledgement is warranted to the following persons, in no particular order, for their assistance in the collection of information, sharing of personal experiences, and technical insight.

Dan Kerns, Manager of Hardsuits Inc. Diving Division, for sharing his experience-base, not only of Atmospheric diving suits but also of Saturation Diving systems.

Kurt Albaugh, consultant for Mustang Engineering, for his industry insight and his mentoring throughout this project.

Dr. Robert E. Randall, Professor Texas A&M University, for his overall guidance and leadership of the project.

John Halwachs, Engineer at Hardsuits, Inc. for his engineering counsel on the atmospheric diving suit.

Jim English, Vice President and General Manager of Hardsuits, and the technicians at Hardsuits International in Vancouver, B.C for the informative visit and trial dive in the shop HARDSUIT.

Tom Bissett, Operations Manager for Hardsuits Diving Division, for all the assistance he provided throughout the project.

Eric Hammans, Dean Parfitt, of Oceaneering's ADS Division and the technicians at Oceaneering for conducting an informative visit of the facilites in Morgan City, LA and for the test tank dive in the WASP.

Phil Nuytten for his acute and innovative insight into the future of the industry and all the feedback provided on this and other projects.

Dena Lee of Mustang Engineering for her enthusiastic support of this project.

Mustang Engineering for their financial support, without which this project could not have been accomplished.

NOMENCLATURE

ADS	Atmospheric Diving Suit, also articulated diving suit, armored diving suit
AUWS	Assesment/Underwater Work System
CSS	Coastal System Staion, Panama City, FL
DCS	Decompression Sickness
DDC	Deck Decompression Chamber
DISSUB	Disabled (or distressed) submarine
DSRV	Deep Submergence Rescue Vehicle
DSSD	Diving Systems Support Detachment, Deep Submergence Unit
DSU	Deep Submergence Unit
ERP	Electric Ring Propulsors
FCT	Foreign Comparative Testing
FSW	Feet of Seawater
GRP	Glass Reinforced Plastic
HPNS	High Pressure Nervous Syndrome
LARS	Launch and Recovery System
MOSUB	Mobile Submarine
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Dive Unit
PTC	Personal Transfer Capsule
ROV	Remotely Operated Vehicle
SCUBA	Self Contained Underwater Breathing Apparatus
SLM	Standard Liter per Minute
SPIDER	Self-Propelled Inspection DivER
SRC	Submarine Rescue Chamber
SRDRS	Submarine Rescue Diving and Recompression System
TMS	Tether Management System

TABLE OF CONTENTS

ABSTRACT iii

DEDICATION iv

ACKNOWLEDGEMENTS v

NOMENCLATURE vi

TABLE OF CONTENTS vii

LIST OF FIGURES ix

LIST OF TABLES x

CHAPTER I: INTRODUCTION 1

- Background 1
- Definition 3
- Classification 4

CHAPTER II: HISTORY OF ATMOSPHERIC DIVING SUITS 5

- Lethbridge and his "Diving Engine" – 1715 (United Kingdom) 5
- Taylor – 1838 (United Kingdom) 9
- Phillips – 1856 (United States) 9
- Carmagnolle – 1882 (France) 10
- Bowdoin - 1915 (United States) 11
- Neufeldt and Kuhnke & the Salvage of the *Egypt* – 1917 (Germany) 12
- Galeazzi – 1930's (Italy) 13
- Campos – 1922 (United States) 14
- Peress and the Tritonia – 1922 (United Kingdom) 14
- Mikalow – 1952 (United States) 15
- Litton – 1967 (United States) 16
- JIM- 1969 (United Kingdom) 16
- WASP – 1978 (United Kingdom) 19
- SPIDER – 1979 (United Kingdom) 19
- NEWTSUIT/HARDSUIT – 1985 (Canada) 20

CHAPTER III: THE MODERN ATMOSPHERIC DIVING SUIT 22

- Advantages of the Modern Atmospheric Diving Suit 22
- Disadvantages of the Modern Atmospheric Diving Suit 26
- Atmospheric Diving Suit Employment 27
- Recent Accident 27
- Parallels with Space Industry 28
- ADS Pilots 29

Future of Atmospheric Diving Suits 30
Next Generation 33

CHAPTER IV: METHODS OF UNDERWATER INTERVENTION 36

Diving Systems 36
Underwater Vehicles 38
Comparison of Specific Underwater Intervention Methods 40
Operational Factors Affecting Intervention Modes 42
Proposal for a comparison of underwater intervention methods 44

CHAPTER V: ROLE OF ATMOSPHERIC DIVING SUITS IN THE NAVIES 46

U.S. Navy – Deep Submergence Rescue 46
French Navy 49
Italian Navy 50

CHAPTER VI: DESIGN CONSIDERATIONS OF THE ADS 51

Introduction 51
Pressure Vessel Design 52
Normal and Emergency Life Support 54
Environmental Controls 56
Heat Transfer Considerations 57
Gas Supply Storage 57
Escape/Safety 61
Additional Considerations 62
Engineering Summary 63

SUMMARY AND CONCLUSIONS 67

Summary 67
Conclusions 68

REFERENCES 69

APPENDICES 72

APPENDIX A: Spreadsheet of ADS Calculations 73
APPENDIX B: Design Drawings of Atmospheric Diving Suit 75
APPENDIX C: Design Comparison to Existing ADSs 80

VITA 82

LIST OF FIGURES

Figure 1: The author in a HARDSUIT 1000 in Vancouver, B.C. 1
Figure 2: The Wrangler, atmospheric diving submersible 3
Figure 3: Classification of underwater intervention methods 4
Figure 4: Diving systems classification 4
Figure 5: Model of Lethbridge "diving engine" 6
Figure 6: Relationship of RMV and O_2 consumption to exertion 7
Figure 7: Relationship of physiological effects to CO_2 concentration and exposure 8
Figure 8: Taylor atmospheric diving suit design, 1838 9
Figure 9: Philips atmospheric diving suit design, 1856 10
Figure 10: Carmagnolle atmospheric diving suit, 1882 10
Figure 11: Bowdoin atmospheric diving suit, 1915 11
Figure 12: Neufeldt & Kuhnke atmospheric diving suit 12
Figure 13: Galeazzi atmospheric diving suit 13
Figure 14: Campos atmospheric diving suit 14
Figure 15: Peress and the Tritonia atmospheric diving suit 14
Figure 16: Mikalow atmospheric diving suit 15
Figure 17: Conceptual drawing of the Litton atmospheric diving suit. 16
Figure 18: JIM suit at Naval Undersea Warfare Center, Keyport, Washington 17
Figure 19: WASP repairing Mariner Energy's Pluto gas flowline at 2,150 feet. 19
Figure 20: SPIDER atmospheric diving suit 20
Figure 21: 'Original' Newtsuit at the Vancouver Maritime Museum, B.C. 21
Figure 22: HARDSUIT 2000 33
Figure 23: EXOSUIT, prototype atmospheric diving suit. 34
Figure 24: Scuba diver 36
Figure 25: Mixed-gas diver 37
Figure 26: Saturation System 37
Figure 27: Nuytco Research Ltd. Deep Worker 39
Figure 28: Max Rover ROV 39
Figure 29: NOAA AUV Odyssey 40
Figure 30: Engineer inspecting HARDSUIT 2000 47
Figure 31: DSRV 2 Avalon being lowered onto USS Greeneville (SSN 772) 47
Figure 32: Submarine rescue chamber 48
Figure 33: HARDSUIT 2000 concept of operations scenario 48
Figure 34: French Navy Newtsuit in a submarine rescue 50
Figure B-1: atmospheric diving suit design drawing (Front view, Mesh) 76
Figure B-2: atmospheric diving suit design drawing (Front view, Solid) 77
Figure B-3: atmospheric diving suit design drawing (Side view, Mesh) 78
Figure B-4: atmospheric diving suit design drawing (Side view, Mesh) 79

LIST OF TABLES

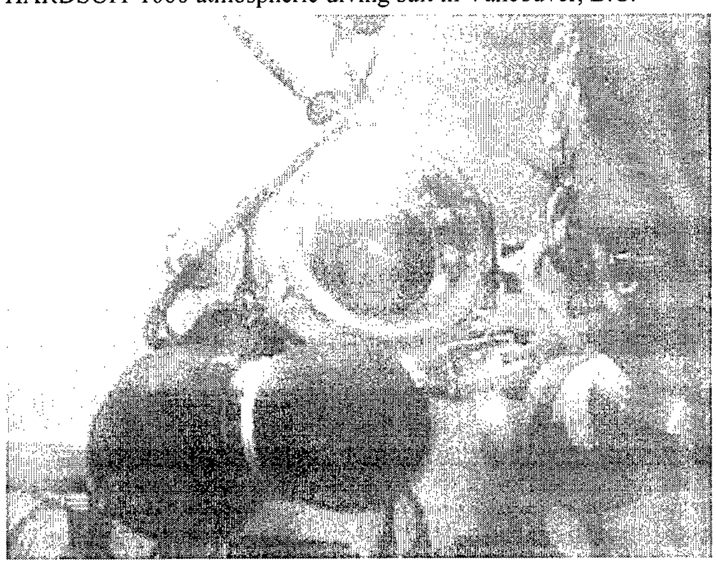
Table 1: Comparison of saturation system, ROV, and ADS 41
Table 2: Considerations in the selection of underwater intervention methods 43
Table A-1: Pressure vessel design spreadsheet 74
Table C-1: Design comparison to existing atmospheric diving suits 81

CHAPTER I
INTRODUCTION

Background

While, the earliest atmospheric diving suits were invented to salvage the gold and other treasures from unfortunate ships, today's atmospheric diving suits are primarily used to support the oil and gas industry's perpetual search for black gold. Figure 1 is an example of the latest development in atmospheric diving suits.

Figure 1: The author tries his 'hand' at manipulating a shackle in the HARDSUIT 1000 atmospheric diving suit in Vancouver, B.C.



John Lethbridge, who is credited with building the first atmospheric diving suit in 1715, for lack of a better term referred to his invention as a "diving engine". It has also been referred to, over its nearly three centuries of existence, as an armored diving suit, armored diving dress, articulated diving suit, one-manned atmospheric diving suit (OMADS), Iron Duke, and a personal favorite is the "Iron Mike". Alfred Mikalow, former owner of the Coastal School of Deep Sea Diving, in his book *Fell's Guide to Sunken Treasure Ships of the World*, even referred to his invention as a deep-sea diving robot. And as best as can be determined from the literature, the term atmospheric diving suit did not come into widespread use until the invention of the JIM suit. With few exceptions, this report uses the now standard atmospheric diving suit, or ADS, to refer to these devices.

Since the days of Lethbridge's "diving engine", before the effects of depth were even fully understood, divers have attempted to isolate themselves from the sea around them, to dive deeper and longer without suffering the physiological difficulties and complications that extreme pressures can have on the human body. In some cases, divers were inspired strictly by the lure of the deep, and in others they were motivated by the treasures it had to offer.

Just as critics condemned putting the first man on the moon, skeptics of the atmospheric diving suit have been heard to say 'if we can do it with robots why risk a human life?' It's not always that simple a question. Remotely Operated Vehicles, or ROVs, have certainly surpassed atmospheric diving suits in their ability to go deeper. Yet, despite a recent ADS pilot fatality, the numbers of atmospheric diving suit incidents have remained negligible. As a matter of fact, until August 1999, there has never been a fatal or serious injury in an atmospheric diving suit. But the risk inherent with the ADS does involve human life, something not usually at risk in ROV operations. There is, of course, a certain risk any time a diver enters the water. The human body was not meant to be subjected to extreme pressures. But with the proper redundancy and safety features built in, it can be argued that your risk of a serious injury is greater by driving your car to work every morning.

Granted, ROVs can undoubtedly even do many of the same tasks deeper, but not always more cost effectively and not usually faster. So it's a question of time as well as technology, and time in the offshore industry means money and usually lots of it. At the current price of oil a barrel at about $30.00 (OPEC Monthly Oil Market Report, July 2000), with often many thousands of barrels per hour at stake until a repair job is completed, hundreds of thousands of dollars in capital is at risk.

However, atmospheric diving suits will never supplant the ROV, or diver. As Dan

---

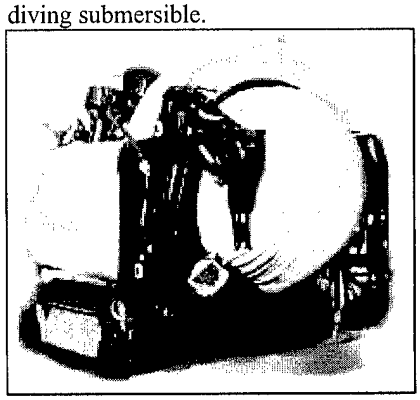
This report follows the style and format of the *Marine Technology Society Journal*, Volume 33, Number 4, Winter 1999/2000.

Kerns, Manager of Hardsuits Incorporated Diving Division, is fond of saying "The ADS is not meant to replace the ROV, diver, or vice versa, its just another tool to put in your bag, and pull out when the logistics, cost-analysis, etc. proves that tool is the one to use." As evidence, Oceaneering's recent record-setting deepwater pipeline repair projects completed in Mariner Energy's Pluto and Dulcimer fields proved a combination of ADS and ROV was the most advantageous technique for getting the job accomplished within time and budgetary constraints (Huber, 1999; Gorman, 2000).

Definition

An atmospheric diving suit, or ADS, is an articulated anthropomorphic single person submersible presently capable of diving to depths of up to 2500 feet while maintaining the internal pressure at or very near one atmosphere. The immediate and obvious advantage of the atmospheric diving suit is its elimination of most of the physiological hazards of ambient pressure divers. There is no need for compression or decompression schedules, no requirement for special gas mixtures, and no danger of nitrogen narcosis or "bends". Likewise, the atmospheric diving suit can venture up and down the water column any number of times without any consequences or delay (Albaugh, 1999).

Figure 2: The Wrangler, atmospheric diving submersible.



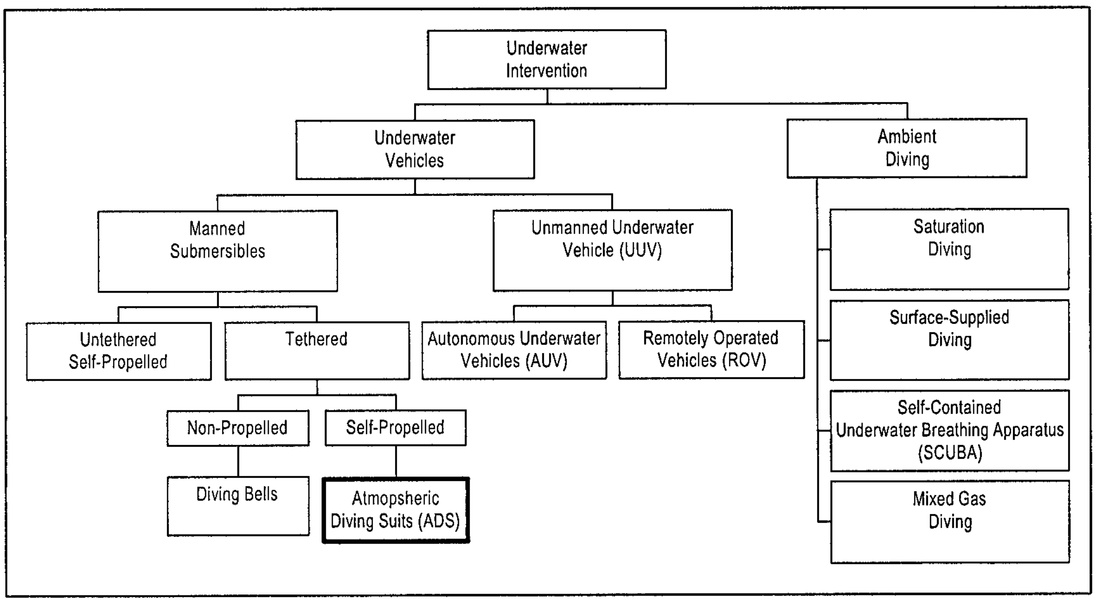
Atmospheric diving suits may have articulated arms and legs, such as the JIM suit and HARDSUIT family of suits, or may have articulated arms only, such as the WASP and SPIDER. It is this feature that distinguishes the atmospheric diving suit from an Atmospheric Diving <u>System</u> (or Submersible). The suit has human powered limbs vice remotely operated manipulator arms. The MANTIS or WRANGLER, as shown in Figure 2, although

manned, would be more correctly described as an atmospheric diving system or atmospheric diving submersible, due to their remotely operated arms. All atmospheric diving suits in use today have a thruster package for mid-water maneuverability.

Classification

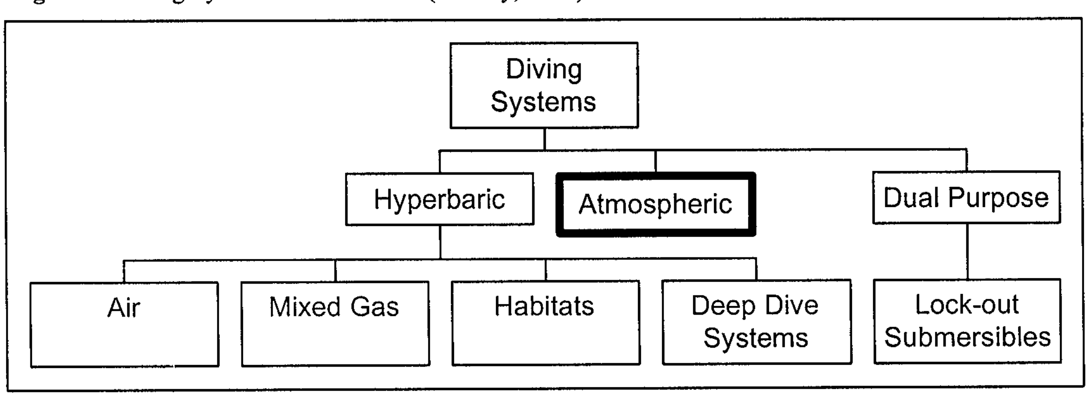
The atmospheric diving suit is a manned submersible and one-atmosphere intervention device, as opposed to an ambient pressure intervention method, such as the saturation diver. Figure 3 is a classification diagram of current underwater intervention methods.

Figure 3: Classification of Underwater Intervention Methods.



The atmospheric diving suit has also been classified as a diving system by many authors as illustrated in Figure 4.

Figure 4: Diving Systems Classification (Hawley, 1996)



CHAPTER II

HISTORY OF ATMOSPHERIC DIVING SUITS

Lethbridge and his "Diving Engine" – 1715 (United Kingdom)

John Lethbridge's 1715 "diving engine, without communication of air", as he called it, is widely considered to be the earliest atmospheric diving suit.

In 1715 at thirty-nine years of age, John Lethbridge, a Devonshire, Englishman was, by his own account, a man with a large family to support (Lethbridge, 1749). Thus, seeking a means to make his fortune, he conspired to build a device with which he might recover the treasures of sunken ships. It was purportedly used successfully on several occasions to as deep as 10 fathoms (60 feet). Lethbridge describes his scheme in a letter to *The Gentleman's Magazine* in September of 1749, as such:

{The italicized excerpts below are in the same style and character as the original}

"…the first step I took towards it was going into a hogshead[1] *upon land, bung'd up tight, where I stayed half an hour without communication of air; then I made a trench near a well at the bottom of my orchard in this place in order to convey a sufficient quantity of water to cover the hogshead and then try'd how long I could live underwater without air pipes, or communication of air, and found I could stay longer underwater than upon land."*

Having completed this experiment he then engaged a cooper in London to make a "diving engine" of the following description:

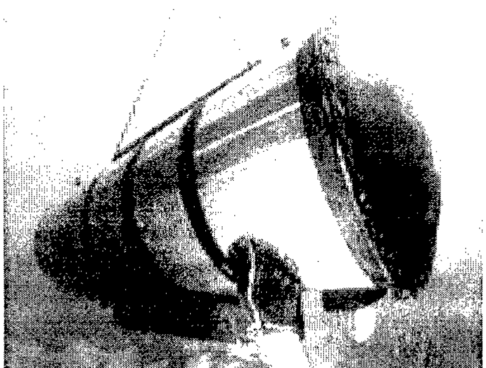
"It is made of wainscot[2]*, perfectly round, about six feet in length, about two foot and a half diameter at the head, and about eighteen inches diameter at the foot, and*

---

[1]hogshead is the old English term for a 54-gallon barrel.
[2]wainscot is joined wooden paneling.

contains about 30 gallons; it is hoop'd with iron hoops without and within, to guard against pressure; there are two holes for the arms, and a glass about four inches diameter, and an inch and quarter thick, to look thro', which is fixed in a direct line with the eye; two airholes, upon the upper part, into one of which air is conveyed, by a pair of bellow, both of which are stopt with plugs, immediately before going down to the bottom. At the foot part there's a hole to let out water sometimes; there's a large rope, fix'd to the back, or upper part, by which it's let down; and there's a little line, called the signal line, by which the people above are directed what to do, and under is fix'd a piece of timber, as a guard for the glass. I go in with my feet foremost, and when my arms are got thro' the holes, then the head is put on, which is fastened with scrues. It requires 500 weight to sink it, and take but 15-pound weight from it, and it will bouy upon the surface of the water. I lie straight upon my breast, all the time I am in the engine, which hath many times been more than 6 hours, being, frequently, refreshed upon the surface, by a pair of bellows. I can move it about 12 foot square, at the bottom, where I have stayed, many times, 34 minutes. I have been ten fathom deep many a hundred times, and have been 12 fathom, but with great difficulty."

Figure 5: Lethbridge "diving engine" model (Courtesy of National Undersea Research Program)



We might never have had the above account, except that a Mr. Samuel Ley had accused Mr. Lethbridge of depriving another man of the previous invention of the same diving engine in the July 1749 issue of *The Gentleman's Magazine.* Mr. Lethbridge emphatically denies this in the most gentlemanly banter he can muster, and then goes on to give the description above.

As documented evidence has shown, and certainly to the delight of his large family, Mr. Lethbridge was reportedly very successful in his endeavor. His first success was in the salvage of the English Indiaman *Vansittart*, which sank in 1718 in the Cape

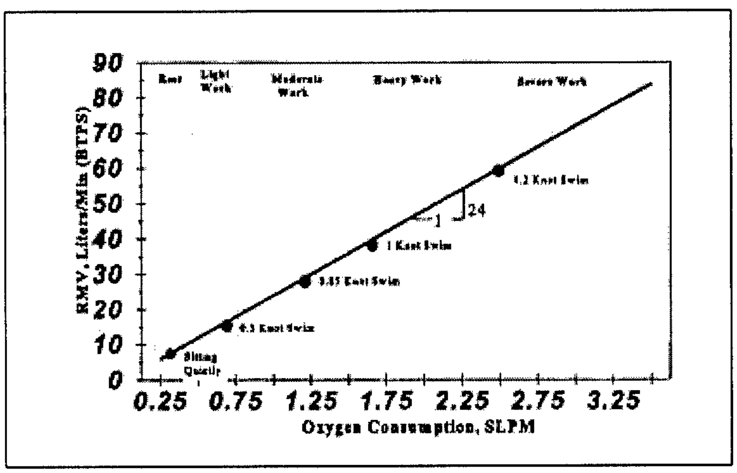
Verdes off the Isle of May (Cowan, 1999). Amazingly Mr. Lethbridge and another early diving hero, Jacob Rowe, recovered incredible amounts of silver from the *Vansittart*. For several years following the *Vansittart* salvage, Lethbridge and Rowe were awarded and salvaged several wrecks for the Spanish, British and Dutch owners (Aylmer, 1996).

One can note from the excerpt and Figure 5 that Lethbridge's arms protruded through the pressure vessel, and were sealed with a leather cuff. Therefore, this suit might be more appropriately called a semi-atmospheric diving suit. It is nevertheless included here, since the technology to create any workable joint to maintain the entire person at one-atmosphere did not, of course, exist yet.

What follows is a mathematical investigation into Mr. Lethbridge's claim of 34 minutes "bottom-time".

Given:

Figure 6: O_2 consumption and respiratory minute volume at varying work rates (Nuckols, 1996)



Vessel interior volume (V_{int}) = 30 gal (UK) *{136.38 liters}* – from excerpt
Time (t) = 34 minutes?

Assumptions:

Light work rate, i.e. O_2 consumption ($\dot{V}_{O_2}$) = 0.3 – 0.5 SLM (from Figure 6)

Respiratory quotient (RQ[1]) = 0.9

Calculating:

Actual time before reaching a CO_2 partial pressure of 10%
(i.e. when Mr. Lethbridge would have reached Zone IV of Figure 7)

---

[1]On a normal diet of carbohydrates, fats and proteins a person will generally have an RQ of ~ 0.82 (Nuckols, 1996)

Using an RQ of 0.9, i.e. CO_2 production is equal to 90% O_2 consumption, therefore:

RQ x $\dot{V}_{O_2}$ = SLM CO_2 production

0.9 x .5 SLM = .45 SLM CO_2 production

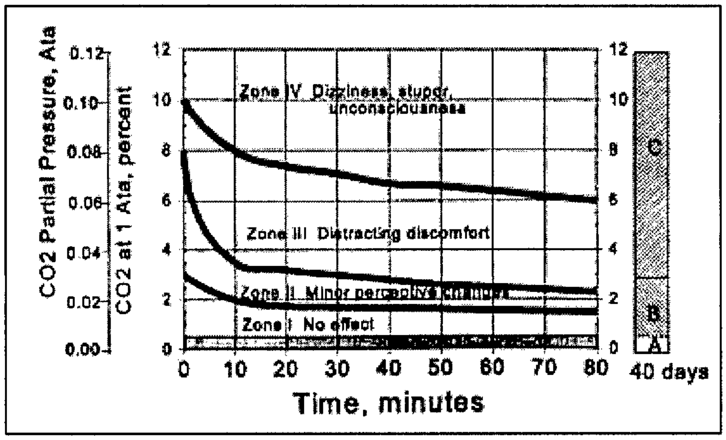


Figure 7: Relationship of physiological effects to CO_2 concentration and exposure period (US Navy Diving Manual)

Subtracting the ~ .033% by volume of CO_2 already present in air (and in the vessel upon submerging).

(10 - .033)/100 x 136.38 = 13.59 liters CO_2

13.59 liters/ .45 SLM = **30 minutes**

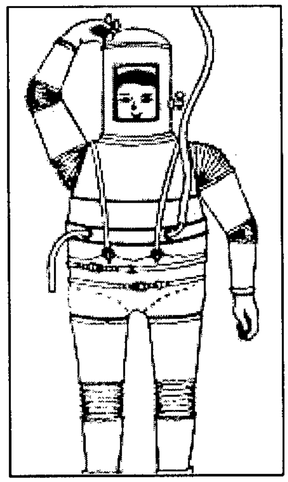
At first glance this would seem fairly close to the claimed 34 minutes, but the assumptions are very forgiving, in that at 0.5 SLM very little work could be accomplished. The calculations also assume a liberal 90% respiratory quotient. Moreover, according to Figure 7, to reach ZONE IV (10% CO_2) Mr. Lethbridge would have had to stay in the vessel to the point of near unconsciousness before exiting. Is this the "great difficulty" Lethbridge was referring to?

With the above generous assumptions it seems unlikely that Lethbridge was actually able to stay submerged for as long as 34 minutes as he claims, especially if he was to accomplish any appreciable work. Of course, as history records, it didn't seem to hurt his fortunes any.

Following Lethbridge and Rowe's exploits there was little to no mention of the armored diving suit until 1838, an almost 80 year lull from Lethbridge's death in 1759. A replica of Lethbridge's "diving engine" is on display at the Heritage Shipwreck Museum of Charlestown, in Cornwall, England.

Taylor – 1838 (United Kingdom)

Figure 8: Taylor atmospheric diving suit design, 1838.



In the year 1838, W.H. Taylor, an Englishman, designed the first known armored diving suit with articulating joints. The suit was to be surface-supplied and had accordion-like joints of spring steel, reinforced and water sealed with leather (Harris, 1985).

From his drawing it seems that either Mr. Taylor had no intentions of his suit being a true atmospheric diving suit, or else he had no understanding of the depth-pressure relationship. Notice that in Figure 8, the suit appears to exhaust directly into the surrounding water from a short hose located at the divers waist. The interior pressure would have, therefore, had to be greater than the water pressure at depth. Secondly, the soft cloth joints of the suit would have most likely collapsed when exposed to any considerable pressure (Davis, 1951).

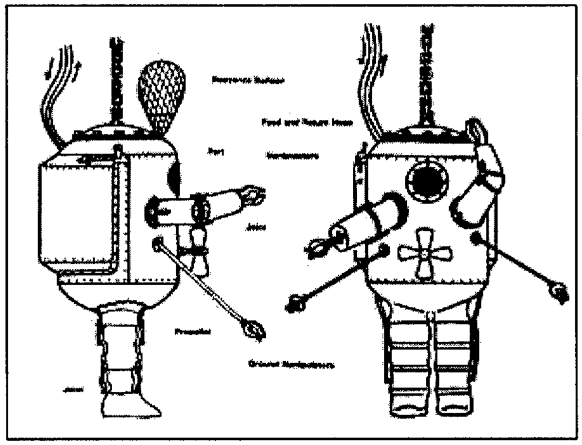
On the opposite side of the Atlantic an American inventor was soon to be at work designing a more promising suit.

Phillips – 1856 (United States)

An American from Chicago named Lodner D. Phillips designed the first completely enclosed atmospheric diving suit in 1856 (Davis, 1951). His design, in Figure 9, consisted of a barrel shaped upper torso with domed ends and was the first to

incorporate ball and socket type joints in the articulated arms and legs. The suit had at least eight joints. The arms each had joints at the shoulders and elbows and the legs had joints at the knees and hips. It had a ballast tank on the back, a single viewing port, a man-hole cover entrance on top, and simple manipulators at the ends of the arms, standard fare on all atmospheric diving suits in use today. Air was to be supplied and exhausted through a twin hose entering near the top of the suit. It included a lifting eye in the center of the hatch cover for hauling it up and down.

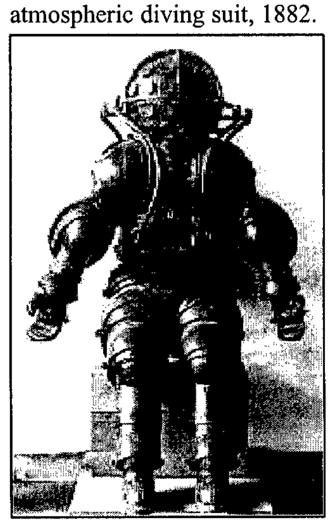
Figure 9: Phillips atmospheric diving suit design, 1856.



Some of the more interesting features were the waist high hand-cranked screw propeller at the front of the suit, the additional manipulators projecting from the waist that extended the operator's reach, and the "buoyancy" balloon attached to the top that would have certainly collapsed with increasing depth.

No record exists to indicate the Phillips suit was ever built but many features of the design can be seen in similar more successful suits over a half a century later. Notably, in January of 1850, Lodner Philips had also been successful at patenting a design for a new submarine (Pesce, 1906).

Figure 10: Carmagnolle atmospheric diving suit, 1882.



Carmagnolle – 1882 (France)

Two French inventors, the Carmagnolle brothers of *Marseilles*, France patented an armored diving dress in 1882. The joints were made of partial sections of concentric spheres formed to create a close fit and intended

to be kept watertight with a loop of waterproof cloth attached to both sections of the joint and folded so as to slide upon itself when the joint was moved (Davis, 1951). The suit, seen in Figure 10, had no less than 22 of these rolling convolute joints; four in each leg, six per arm, and two in the body of the suit. The suit was the first truly anthropomorphic suit design to be constructed.

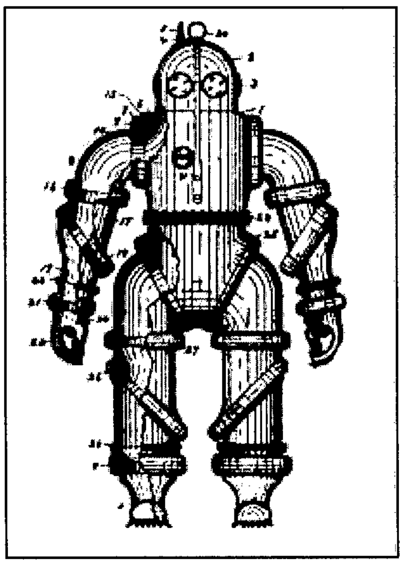
Another distinctive feature of the Carmagnolle suit was the helmet. It had 25 individual two-inch diameter glass viewing ports spaced at the average distance of the human eyes. An additional port at the top of the helmet could be removed to ventilate the suit when at the surface.

The Carmagnolle suit was a brilliant design for its time, incorporating tenets of human engineering not yet the standard, though it would have suffered from many problems. However, the basic joint design was likely sound at minimal pressure, and was demonstrated years later by Litton Industries on hard carapace space suits. The Carmagnolle suit is on display at the National Maritime Museum in Paris.

Bowdoin - 1915 (United States)

Harry L. Bowdoin of Bayonne, New Jersey, received a patent in 1915 for a new type of oil-filled rotary jointed armored diving suit. The joints had a small duct leading to the interior of the joint to allow the external and internal pressure to equalize. However, without constant lubrication the joints would have most likely quickly run dry and prevented rotation of the joint (Harris, 1985). The suit was designed to have four joints in each arm and leg and included one joint in each thumb, for a total of eighteen. Disconnecting the upper and lower halves made entry into the suit possible. The addition of

Figure 11: Bowdoin atmospheric diving suit, 1915.

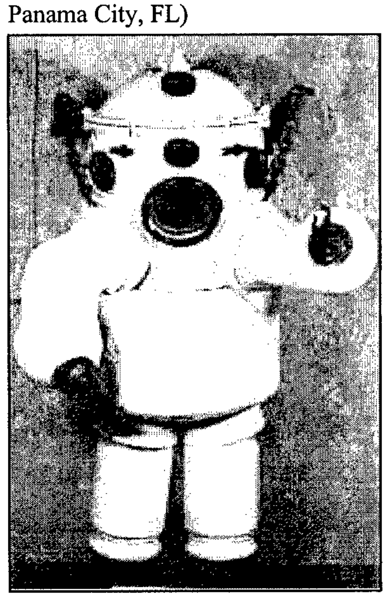


spacers in the waist, arm and legs would have made it possible to accommodate various operators. Four small viewing ports and a single built-in chest mounted lamp facilitated underwater viewing. Figure 11 is Bowdoin's patent drawing for his atmospheric diving suit. Unfortunately, there is no evidence that Bowdoin's suit was ever built.

Neufeldt and Kuhnke & the Salvage of the *Egypt* – 1917 (Germany)

In 1917, the German firm Neufeldt and Kuhnke built two atmospheric diving suit models based on their patented ball and socket joint, which utilized ball bearings to transfer the pressure load. The German Navy tested the second-generation suit to 530 feet in 1924 but limb movement was very difficult and the joints were not "fail-safe." Even so, the suit afforded intervention at previously unheard of depths. The German Navy, reportedly had several Neufeldt and Kuhnke suits, called "Panzertaucher", translated armored diver, during World War II, which later found their way into allied hands after the war. There are unconfirmed reports that the Russian Navy even built copies. The Italian dive helmet designer, Roberto Galeazzi, also obtained the rights to build an atmospheric diving suit system based on the Neufeldt and Kuhnke joint design (Scott, 1931).

Figure 12: Neufeldt & Kuhnke atmospheric diving suit, 1930's (Courtesy Man-in-the-Sea Museum, Panama City, FL)



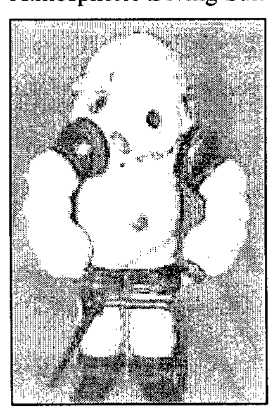
The Neufeldt and Kuhnke suit had joints at each shoulder, one at each thigh and ankle and small ball joints for the mechanical 'pincers'. The joints were sealed by means of a rubber skirt that attached to the socket and slid over the ball. Separation and mobility of the ball and socket joint was achieved by ball bearings between the two. The waist of the suit included a ballast tank that could be filled with water or blown clear with compressed air.

The Neufeldt and Kuhnke suit achieved its fame as a valuable assistant in the salvage of gold and silver bullion from the *S.S. Egypt*. Though the suit was relegated to a mere observation chamber at the depth of the *Egypt*, it was used successfully to direct the mechanical grabs that tore their way to the bullion in the strongholds below (Scott, 1932). The 8,000 ton Peninsular and Oriental liner *Egypt* sank in May of 1922 while outward bound from London to Bombay in a dense fog after a glancing blow, on the port side slightly aft of amidship, from the French freighter *Seine* about 25 miles southwest of Ushant. The Egypt sank in less than 20 minutes and 96 souls were lost. She had aboard approximately five tons of gold and two tons of silver. The Italian firm, Sorima, Societa Recuperi Marittimi, or Maritime Salvage Company, conducted the salvage. To reduce the chance of leakage, the suit was first simplified in the number of joints, to one at each shoulder and two in each leg, and later the suit was completely replaced by an even simpler observation-only chamber. Figure 12 shows the suit as used by Sorima. Despite this and the fact one of the salvage vessels was destroyed by an explosion killing 12 men, Sorima, recovered over a $1,000,000 in gold and silver ingots in 1932 with the help of the Neufeldt and Kuhnke suit. There is at least one surviving Neufeldt and Kuhnke suit on display at the Man-in-the-Sea Museum in Panama City, FL.

Galeazzi – 1930's (Italy)

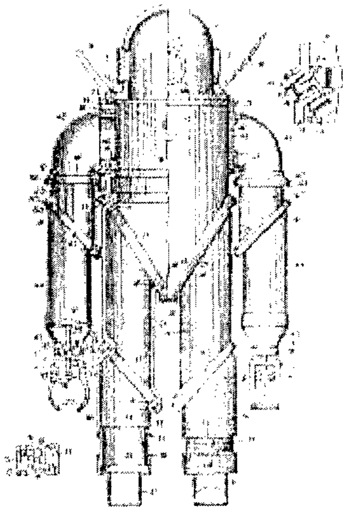
Roberto Galeazzi, a famous diving helmet inventor, received a license to produce and market a suit based on the Neufeldt and Kuhnke joint. There were reputedly more than fifty of the Galeazzi suits built (Harris, 1985). According, to Jim English, Vice President and General Manager of Hardsuits International, the Galeazzi suit can be seen all over Italy, unfortunately decorating the entrances of there Naval bases. At least one, pictured in Figure 13, stands in the Museo Nazionale delle Attivitȧ Subacquee (National Museum of Underwater Activities) in Ravenna, Italy.

Figure 13: Galeazzi Atmospheric Diving Suit



Campos – 1922 (United States)

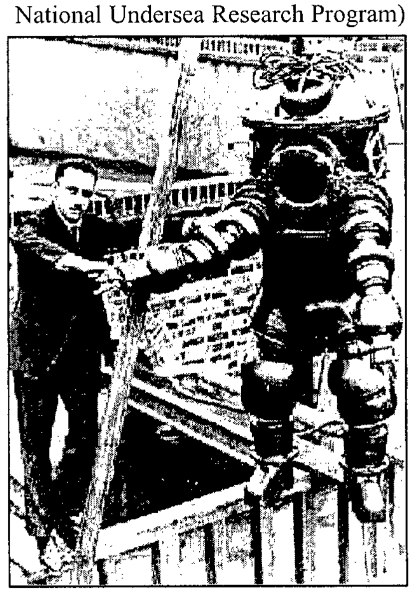
Figure 14: Campos atmospheric diving suit, 1922



In 1922, Victor Campos of New York, patented an atmospheric diving suit with oil-filled rotary joints. The suit was reportedly taken to a depth of 600 feet (184 m). Though the suit could have reached 600 feet, the joints would have most likely not had any appreciable movement (Davis, 1951). However, as mentioned previously, such suits were sometimes used quite successfully as observation chambers. The Campos joint was a fail-safe design, in that if the joint were to fail it would automatically seal and not allow water to enter the suit. Figure 14 is Campos' patent design drawing.

Peress and the Tritonia – 1922 (United Kingdom)

Figure 15: Peress and the Tritonia Atmospheric Diving Suit (Courtesy of National Undersea Research Program)



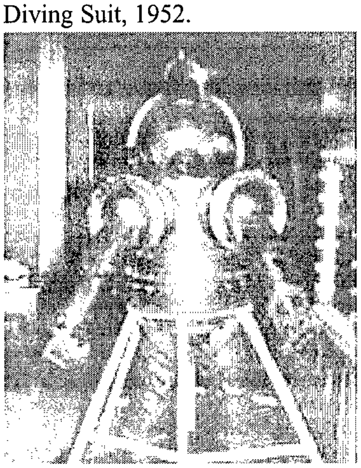
Joseph Salim Peress, later referred to as "Pop" Peress, relocated to Paris in 1912 as an aircraft designer (Taylor, 1997). In 1922, Peress patented the first spherical type joint, which used a fluid to transfer the pressure. He went on to build his first suit in 1925 which unfortunately, did not operate successfully. Peress later redesigned the joints on an annular cylinder and piston resting on a cushion of fluid, which came to be known as Type 1 (Harris, 1985). In 1932 he built a second atmospheric diving suit, what was then referred to as the Tritonia, and is now commonly called "Jim I". Mr. Peress and the Tritonia are pictured in Figure 15. It was successfully used on the wreck of the Lusitania, at a depth of 312 feet (Loftas, 1973). In 1937 the Tritonia successfully completed trials with the British Royal Navy, but the Navy then concluded that there

was no current requirement for deep sea diving and was more interested in developing ambient pressure diving systems.

Peress' expertise is harnessed later in the century to help develop the JIM Suit, named after Peress' chief diver Jim Jarrett. The second suit Peress' built is on display at the British Science Museum in London. 'Pop' Peress died June 4th 1978.

Mikalow – 1952 (United States)

Figure 16: Mikalow Atmospheric Diving Suit, 1952.

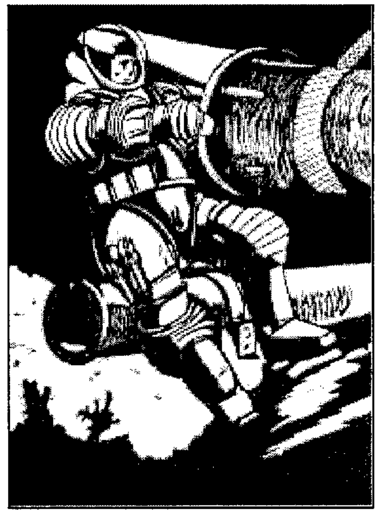


During a period of history considered by many to be a gap in the development of the atmospheric diving suit, Alfred A. Mikalow, once director and owner of the Coastal School of Deep Sea Diving, in Oakland, California, designed and built an atmospheric diving suit (Figure 16). His suit, employing ball and socket joints, was built for the purpose of locating and salvaging sunken treasure. The suit was reportedly capable of diving to depths of 1000 feet and was used successfully to dive on the sunken vessel, *City of Rio de Janeiro,* in 328 feet of water near Fort Point, San Francisco, California (Rieseberg, 1965).

The Mikalow had several interchangeable instruments that could be attached in place of the usual manipulators at the end of the arms. The "deep-sea diving robot", as it was called in *Fell's Guide to Sunken Treasure Ships of the World*, carried seven 90 cubic feet high-pressure cylinders to provide the breathing gas and control the buoyancy. The ballast compartment covered the air cylinders and opened at the bottom near the diver's legs. The suit used hydrophones as its primary means of communication with the surface and powerful searchlights were attached to the head and arms.

Litton – 1967 (United States)

Figure 17: Conceptual drawing of the Litton atmospheric diving suit.



In the late 1960's Litton Industries Space Science Laboratories announced the development of a new design of an atmospheric diving suit (Figure 17) capable of operating to depths of 600 feet (Fonda-Bonardi, 1967). The UX-1, for underwater experimental, suit was to use a combination of constant-volume convolute joints and rotary joints. Their basic principle was to place the geometric axis of the suit joints as close as possible to the anatomical axis of the operator's articulation. The suit design surpassed any that had been built to date, though it never made it to production. In 1974, prior to inventing the Newtsuit, Phil Nuytten bought all rights and patents to the Litton suit (Harris, 1985).

JIM- 1969 (United Kingdom)

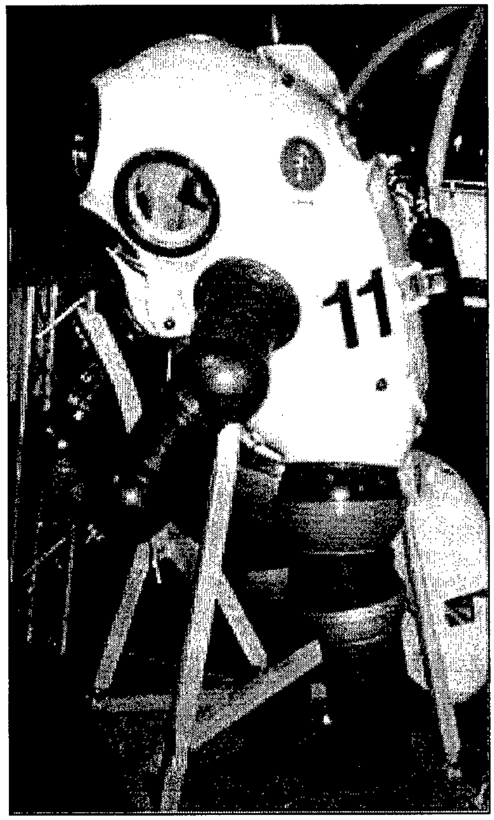
It was not until the 1960's, when commercial diving was unable to keep pace with the petroleum industry's race to deeper waters, that interest was renewed in developing an improved atmospheric diving suit (Baton, 1973).

Mike Humphrey and Mike Borrow, partners in the English firm Underwater Marine Engineering Ltd., recognized the value atmospheric diving suits could bring to the offshore industry. By happenstance they were able to locate and convince Joseph Peress, inventor of the Tritonia atmospheric diving suit to join them (Burrow, 1973)

The old Tritonia was located in a factory in Glasgow and shipped under the "utmost" secrecy - the crate apparently arrived with the words "Lusitania Diving Suit" in large block letters along the side, so much for trade secrets (Morrison, 1989). The suit was still dive-able and required only minor refurbishing before "Pop" Peress

himself in his late 60's demonstrated the suit in a tank in Hampshire. After a lack of financial support from the oil and gas industry, a research grant was secured from the British government to proceed with their plan (Loftas, 1973). DHB Construction, for Dennison, Hibberd and Borrow, was formed to develop the suit. Dr. David Dennison was principally responsible for developing the life-support system, Hibberd provided financial support, and Mike Borrow was the firm's director (Harris, 1985).

Figure 18: JIM suit at Naval Undersea Warfare Center, Keyport, Washington.



The first suit was completed in November 1971 and underwent trials aboard *the HMS Reclaim* in early 1972. Two dives were conducted in excess of 400 feet, limited only by the depth of the ambient divers providing support. Development and testing continued until March 4, 1974 when Mike Humphrey conducted a 'chamber' dive to the equivalent of 1000 feet. Despite the successful testing the offshore petroleum industry still expressed little interest in the ADS. It wasn't until 1975 when Oceaneering acquired DHB Construction and garnered the exclusive rights to the application of JIM suits in the oilfields that JIM became successful (Fridge, 1977). In 1976 the JIM suit was used for a series of four dives on PanArtic's Hecla M25 well (English, 1978). The dives were made through a hole cut in the 16 feet thick ice floe, on which the rig was positioned. The first dive, made by Walt Thompson of Oceaneering, set a record for the longest working dive below 490 feet. It lasted 5 hours and 59 minutes at a depth of 905 feet. The Arctic dives proved that JIM was capable of performing oilfield operations in very cold and very deep water. Average water temperature at the wellhead was measured at 29°F, while the average internal suit temperature was about 50°F. The operators simply wore a heavy wool sweater for

thermal protection. The following year the JIM suit was used on over 35 jobs with an average duration of over 2 hours and depths varying from 300 – 1130 feet (Earls, 1979). By 1981 there were 19 JIM suits in existence.

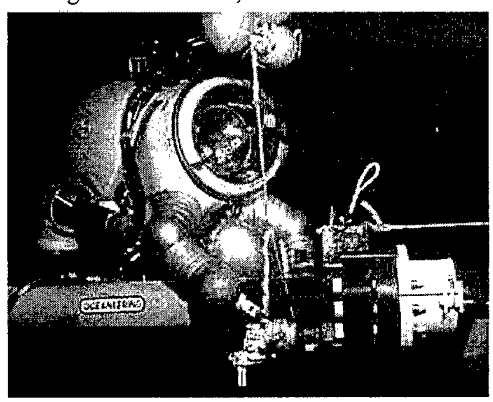
The first JIM suits were cast of magnesium due to its high strength-to-weight ratio and weighed around 1,100 lb in air including the diver. The corrosion problems with magnesium were averted by careful surface preparation and coating. The suit had an in-water weight of 15-50 lb negative buoyancy. A jettisonable-ballast was attached to the front of the suit that could be operated from within the suit. Releasing the ballast would propel the operator to the surface at approximately 100 feet per minute. The suit also included a communication link and jettisonable umbilical. The original JIM suit had eight of the annular oil-supported universal joints, one in each shoulder and lower arm, and one at each hip and knee. Eventually, the magnesium casting was replaced with fiberglass construction and the single joints evolved into many segmented joints, individually allowing only seven degrees of motion, but added together gave the operator a greater range of motion. Additionally, the four port dome was replaced by a transparent acrylic one that allowed the operator a much-improved field of vision. The fiberglass suit was known as the JAM suit. A lighter more anthropomorphic suit was built of aluminum or glass-reinforced plastic and known as the SAM suit. The aluminum model was rated to 1000 feet and the fiberglass suit was rated to 2000 feet.

Every technology has a defining point when it becomes wholly viable to the market it wishes to serve; for the atmospheric diving suit - the JIM suit was that defining point. During no period prior to JIM was the atmospheric diving suit used as extensively or successfully as a means of underwater intervention. The suit was the basis of a new generation of suits that would prove their worth for many years in the oil industry and elsewhere. Rightfully so, there has probably been more written about the JIM suit than any other atmospheric diving suit developed. There are several versions of the JIM suit, such as in Figure 18, on display at museums throughout the U.S. and the U.K.

WASP – 1978 (United Kingdom)

The WASP was developed and built by Graham Hawkes of Offshore Submersibles (OSEL), formerly of the UMEL/DHB consortium. After successful legal action Oceaneering prevented OSEL from selling the WASP, alleging that Hawkes had developed the suit while still working for UMEL (Harris, 1985). Interestingly enough, prior to the legal battle, the contract for the first WASP suit was to Wharton Williams, a firm that later was instrumental in the development of the SPIDER, an ADS strongly resembling the WASP. The first two WASPs were built and in operation in mid-1978 (Ocean Industry, 1977). It is similar in design to the JIM suit except below the waist it has a glass reinforced plastic cylinder in place of articulated legs. Small multi-directional thrusters, controlled by foot pedals within the cylinder, gave the WASP more mobility. Although the developers of the JIM suit experimented with a thruster-pack earlier, the WASP was the first suit to successfully apply thrusters allowing the ADS a mid-water capability not present before.

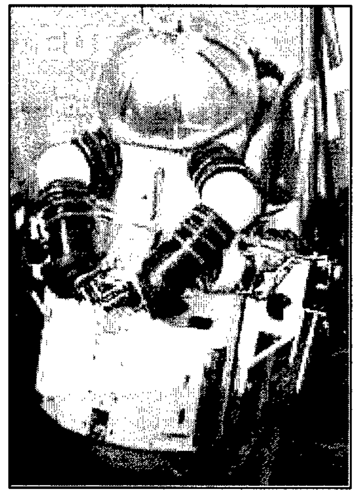
Figure 19: WASP installing an in-line bolted flange spool-piece to repair Mariner Energy's Pluto gas flowline at 2,150 feet.



Oceaneering's WASP has led the field in deepwater repair, setting what is claimed to be a new working water depth record for an on-bottom pipeline repair project. The pipeline repair, completed at 2150 feet, was made to an eight-inch gas pipeline connecting a well in Mariner Energy's Pluto field to a platform 29 miles away (Figure 19). The job was performed using the WASP and Oceaneering's 150HP Millennium ROV, illustrating the effectiveness of the ADS and ROV in tandem (McCabe, 2000).

SPIDER – 1979 (United Kingdom)

Figure 20: SPIDER ADS (Courtesy of Silvercrest Submarines)



Wharton Williams Ltd. and Vickers Slingsby Ltd. developed the SPIDER (Self-Propelled Inspection DivER) in the 1970's, in answer to the WASP (figure 20). The basic design was very similar to the WASP, in that it had segmented ball and socket arm joints, a hemispherical pressure vessel for the legs and a 360° viewing dome (Wharton, 1979). One of the SPIDER's unique features were the two hydraulically operated suction pads, 'sticky feet', located in the equipment package that were intended to allow the SPIDER to attach itself to any relatively smooth surface, that is if you can find one in the barnacle encrusted sea. Additionally, rather than the 'standard' mechanical advantage manipulators found on other atmospheric diving suits, the SPIDER had hydraulically operated manipulators. An adjustable pressure relief valve permitted varying the grip pressure. Like the WASP, the SPIDER also has variable ballast control. Two SPIDERs, owned by Silvercrest Submarines, are currently operating in Hawaii in support of a scientific research program.

NEWTSUIT/HARDSUIT – 1985 (Canada)

Phil Nuytten developed the NEWTSUIT, after leaving Oceaneering in the 1980's, based on a rotary joint he patented in 1984. The NEWTSUIT, built by Hardsuits International – at present a subsidiary of Stolt Offshore, and now called the HARDSUIT, is a truly anthropomorphic suit with articulated arms and legs and just enough room for the operator to pull his arms back into the body of the suit to operate interior controls. The suit is capable of a wide range of motion enabling it to enter some spaces previously accessible only to divers. The original NEWTSUIT, as seen in Figure 21, is now on display at the Vancouver Maritime Museum, B.C.

There are currently three versions of the HARDSUIT available: the original cast aluminum 1000 foot version (HARDSUIT 1000) of which 17 are in service; six

Figure 21: 'Original' NEWTSUIT at the Vancouver Maritime Museum, B.C.

versions rated to 1200 feet (HARDSUIT 1200); and a forged aluminum 2000 foot version (HARDSUIT 2000) recently delivered to the U.S. Navy for its submarine rescue program. Additionally, due to the differences in commercial certification and U.S. Navy certification criteria, a commercial version of the HARDSUIT 2000, to be designated the HARDSUIT 2500, will be available to the industry and certified to a depth of 2500 feet.

The HARDSUIT has 16 (four in each arm and leg) patented hydraulically compensated rotary joints that allow the pilot to physically move the arms and legs of the suit. In many of the suits operated by Hardsuits the hip joint has been rendered immobile, presumably because it provided little additional mobility. Manually operated manipulators at the end of each hand pod allow the pilot to grasp and maneuver objects underwater. Two 2.25 HP thruster modules, are controlled by footpads within the suit permitting the pilot to "fly" from point to point or maintain station within a light current. The suit's life support system allows it to work at depths of 2000 feet for up to six hours, with additional emergency life support for up to 48 hours. It has no battery back-up for its thrusters, and therefore it's Stolt Offshore's policy to limit operations to water depths not greater than the depth rating of the suit. The suit opens at the waist for entry and exit. Extensions can be inserted in the legs and arms of the suit to accommodate most any size operator.

CHAPTER III

THE MODERN ATMOSPHERIC DIVING SUIT

The modern atmospheric diving suit has evolved over a period of over 200 years to provide a useful method of underwater intervention. The basic premise though is unchanged; separate divers from their environment while still allowing them to complete work. Likewise, with everything there are advantages and disadvantages. While most of the advantages where as true in Lethbridge's day as they are today, it was well after Lethbridge that the advantages began to be thoroughly understood, specifically those related to the physiology of diving.

Advantages of the Modern Atmospheric Diving Suit

As mentioned previously, the primary advantage of the atmospheric diving suit concerns the elimination or lessened severity of the physiological hazards generally associated with ambient diving. In order to adequately comprehend this advantage, these hazards are first examined.

Physiological Hazards of Diving

Hypoxia

Hypoxia, or oxygen shortage, is a condition in which the body's cells fail to receive enough oxygen to support their normal metabolic functions. Hypoxia can result from an inadequate amount of oxygen in the breathing gas and unconsciousness usually results from partial pressures of oxygen less than 0.10 atm (Nuckols, 1996).

Hypercapnia

Hypercapnia is a result of excess carbon dioxide in the blood. This condition may result from an excessive level of carbon dioxide in the breathing medium or by the inadequate removal of CO_2 in closed or semi-closed breathing systems. Figure 7 as shown previously illustrates the effects of carbon dioxide concentration versus exposure period.

Asphyxia

Asphyxia describes the presence of both hypercapnia and hypoxia.

Carbon Monoxide Poisoning

Carbon monoxide (CO) poisoning may result, because CO has an approximately 200 times greater affinity to hemoglobin in the blood than O_2 does (Nuckols, 1996). Blood concentrations of CO to high may impede the vital transport of O_2 to the cells. Symptoms may include abnormal redness of the lips and fingernails, headaches, nausea and vomiting.

Nitrogen Narcosis

Nitrogen narcosis, often referred to as "rapture of the deep", is due to the narcotic effects of nitrogen at elevated partial pressures. Symptoms are comparable to alcoholic intoxication. On standard air, at depths of 100 FSW the effects of nitrogen narcosis are first noticed and may include lightheadedness and euphoria. As the depth increases the narcotic effect is amplified and at 200 FSW simple tasks usually cannot be performed correctly. Greater than 350 FSW unconsciousness may result (Randall, 2000). Nitrogen is typically replaced with helium for dives beyond 200 FSW. Helium also has anesthetic properties but they occur at much greater depths.

Decompression Sickness

Decompression sickness (DCS) results from super saturated gases in the body being brought out of solution to quickly leading to the formation of bubbles in the tissues or blood stream. This effect is analogous to the bubbles that form when first opening a carbonated drink. Symptoms may include pain in the joints due to bubbles in the tissues, to paralysis or death from pressure on the central nervous system or from a gas embolism due to the blockage of blood flow to the brain. Treatment involves the recompression of the diver and may be prevented by adhering to decompression tables.

High Pressure Nervous Syndrome

High-pressure nervous syndrome (HPNS) may be characterized by dizziness, nausea, vomiting, tremors and convulsions. HPNS generally occurs at depths greater than 600 FSW and worsens with increased depth and the faster the rate of compression (Nuckols, 1996). HPNS was initially referred to as helium tremors since it was first observed in heliox (helium and oxygen) mixtures. Methods of preventing HPNS include using a slow and steady rate of compression and adding other inert gases such as nitrogen to helium/oxygen mixtures (trimix).

Barotrauma

Barotrauma refers to maladies resulting from the mechanical effects of high pressure on the human body and usually results due to the failure or inability to equalize pressures in the bodies natural air spaces, such as the ears, sinuses, and teeth.

Accordingly, by enclosing the diver in a 'submersible' at one atmosphere of pressure, most of these hyperbaric problems can be completely eliminated.

Other advantages of the atmospheric diving suit include:

- A major advantage of the ADS, specifically over the ROV, is the ability to put a person directly at the worksite where they are most effective in improvising. Additionally, the ADS has a greater dexterity and much better depth perception than the ROV.

- No Decompression. No lengthy decompression, or compression, is necessary. Therefore the ADS can get to the worksite and return much faster than the ambient diver.

- Multi-level dives. The ADS may make unlimited excursions up and down the water column to any depth required within its rated depth. Unlike saturation divers who have a limited safe excursion range from their working depth.

- Mid-water capability. The thruster package gives the ADS a mid-water and moderate current capability.

- Up-front engineering. Minimum or no pre-engineered tooling is required and often, standard diver tooling may be used.

- High altitude diving. The ADS eliminates the need for special high-altitude deep-diving decompression tables and is especially useful in sites where access may be limited or impractical for a saturation system.

- Longer bottom times. The ADS may stay at the worksite for periods of six hours or more if necessary.

- Peripherals. The ADS may carry to the worksite many of the features of ROVs, such as lights, cameras, sonar, and basic tools.

Disadvantages of the Modern Atmospheric Diving Suit

The disadvantages of ADSs are as with any 'submersible', they still separate the human, or more specifically the human's primary mechanical tool - his hand, from the task. Since the ADS operator's hands are separated from the environment by the suit and it's manipulators they have little or no real feedback and must rely mostly on sight to effectively operate. This leads to another important disadvantage of the ADS - it can't work well in extremely turbid waters. This is significant considering most working dives are never conducted in completely clear and calm water, and divers oftentimes need their sense of touch in order to complete their mission.

Other disadvantages include:

- Limited payload. The ADS is generally less capable than the ROV in carrying payloads.

- Limited access. As compared to the diver, and small work class ROVs, the ADS's ability to access confined spaces is limited.

- Surface Support. In terms, of surface support the ADS requires less support than saturation system, but more than the average ROV work package.

- Deck Space and Weight. The ADS footprint and load generally follows that of surface support; less than saturation systems but more than ROVs.

Additionally, as mentioned previously, putting the human operator at the work site is also a concern in terms of risk and safety, and must be considered during project planning.

A current cost comparison and abbreviated capabilities comparison of the portable saturation system versus the atmospheric diving suit versus the remotely operated

vehicle also follows in the Chapter IV discussion of other underwater intervention devices.

Atmospheric Diving Suit Employment

The majority of atmospheric diving suit use is in the offshore oil and gas industry, but the atmospheric diving suit has also seen use in salvage, high-altitude diving, and oceanographic research.

Some of the proven applications of the Atmospheric Diving Suit in the offshore arena are:

- Platform inspection
- Anode replacement
- Cathodic protection and thickness readings
- Crack detection
- Riser clamp installation
- Pipeline inspection
- Rigging and salvage
- Flooded member detection
- Hydraulic tool operation
- Pipeline tie-ins
- Marine salvage
- Inland water inspection

Consequently, after a period of 30 years it has been reintroduced, this time successfully, to the U.S. Navy for use in its Deep Submergence Rescue Program. Other international Navies are also employing the atmospheric diving suit to assist a distressed submarine. See Chapter V for more information about the role of the atmospheric diving suit in the Navies.

Recent Accident

On August 29th, 1999 an Oceaneering operated WASP, in the Garden Banks 161 field of the Gulf of Mexico, dropped approximately 80 ft while being lowered from its launching mechanism (Ocean Oil Weekly Report, 1999). A bolt sheared dropping the

WASP and pilot 80-ft. The suit was believed to have struck the launch platform during the fall and an arm joint was compromised, flooding the WASP. The WASP was in a head down attitude. The pilot, Jay Shapcotte, did not survive. Subsequent investigations of the bolt indicated a hairline fracture. According to Oceaneering, the launching mechanism was load-tested and approved by Lloyd's Register prior to the accident. Similar bolts on all identical launching structures were inspected and no abnormalities were found. The US Coast Guard conducted the investigation. The suit was being operated from the Ocean Ambassador drilling rig. As reported in Offshore Magazine in 1999, prior to this incident Stolt Offshore (Hardsuits) and Oceaneering had zero lost-time accidents in their atmospheric diving suits. Even following last years fatal accident in the WASP, many in the industry still assert, based on all types of atmospheric diving systems (not including military applications), that atmospheric diving is still the safest type of diving known to man.

Parallels with Space Industry

In a Society of Automotive Engineers Technical paper, Phil Nuytten draws a comparison between the quest to send people into outer space versus the quest to send divers to the great depths of the ocean (Nuytten, 1984). The romanticism of sending a person to the moon, and being the first, was an idea an entire nation embraced. With his special message to congress, on May 25 1961, John F. Kennedy instituted that race and America became that nation. Likewise, John F. Kennedy played a significant role in the advancement of 'inner' space exploration. His less famous mandate to "tap the ocean depths" spurred initial progress in undersea exploration. Though, statistics still indicate there is a significant disparity between the time and resources spent exploring our own underwater backyard to those spent in reaching distant moons and planets. In fact, even the oceanographic community's expertise is being used to assist in the effort to find life on distant planets. Moreover, to the scientist, deepwater is practically as remote as the moon.

Astronauts, wisely, train for the weightlessness of space in huge water tanks. Scott Carpenter, was possibly the first dual space'naut - an aquanaut and astronaut, when he became involved with the Navy's SEALAB project in the 1960's. According to Robert Ballard, one of the greatest ocean explorers of our time, less than one percent of the deep sea has even been seen, much less fully explored (Earle, 1999). Statistics abound regarding the disparity between outer-space exploration and inner-space exploration. Dr. Sylvia Earle, noted marine biologist and ocean explorer, even suggests we may land a man on Mars before ever returning to the Challenger Deep, the deepest point in the ocean.

Divers and astronauts both operate in unnatural environments for man and require some method of physical protection to operate in those environments. These environments cannot sustain human life for any great length of time without isolating at a minimum the breathing system from this environment. Yet these environments also allow the inner space and outer space man to move freely in three-dimensions.

Litton Space Industries was well aware of this semblance of environments, when they designed an atmospheric diving suit intended for diving to depths of 600 feet, in the late 1960's. Though it never made it to full-scale production, it was arguably the most well designed suit for its time period. Like Litton, NASA's Ames Research Center and Johnson Space Center all once built and tested 'hard suits' for use in outer space.

ADS Pilots

They are called 'pilots' and their job is to fly, but it's not airplanes they're flying and it's not the wild blue yonder. They are divers with special training that allows them to soar to the 'deep blue yonder' in atmospheric diving suits. Unlike the typical ambient diver they are not subjected to the extreme pressures of depth and all the physiological

hazards associated with it. They remain at one-atmosphere of pressure throughout the dive, separated from the environment by a rigid hull with articulated arms and legs.

The pilots control the movement of the suit by pedals in the feet of the suit that controls four back-mounted thrusters. In the HARDSUIT, by pressing up or down on the right foot pedal, pilots control the horizontal motion of the suit. By pressing up or down on the left foot pedal they control the vertical motion of the suit. And by pressing on the instep or outstep of the right pedal you can spin around the vertical axis of the suit. The WASP operates similarly by pedals, but its pedals are segmented with a small non-functioning footrest at the center of the pedal that permits the support of the diver's own weight.

Jim English, of Hardsuits, says, that "it takes a diver approximately 20 hours of training in the suits to become comfortable with the controls and manipulators" and many more to become proficient. In fact, experienced pilots may even have the finesse to retrieve quarters from the bottom of a test tank with their manipulators. The specially designed manipulators allow the pilots to operate most underwater tools, with little or no pre-engineering.

Dr. Phil Nuytten envisions a day when anyone that can afford one will have an atmospheric diving suit in their closet and will dive the deeps just as the trained operators in the offshore industry do today. The complexity of the ADS makes it difficult to imagine, but Dr. Nuytten is currently working on a 300ft swim-able version called the EXOSUIT. Due out next year, the dexterity of the EXOSUIT, according to Dr. Nuytten, will be such that average-build users could propel it through the water with their own arms and legs vice a thruster package.

Future of Atmospheric Diving Suits

Trend toward deepwater operations

The industry is pushing to develop reserves in deeper and deeper waters. According to *The World Deepwater Report 2000-2004* prior to 1960, 200 feet was the maximum water depth from which oil and gas was produced, by 1990 this had passed 2000 feet and by 2004 the maximum depth is expected to be over 7000 feet. In fact, according to a Stolt Offshore Press Release, Petrobras broke a world record in September 1999 by successfully drilling a well in the world's deepest water. The record breaking well, RJS 540, is located in a water depth of 8543 feet in the Campos Basin. Additionally, as reported in Underwater Magazine, the average depth for subsea wells up to 1999 was 600 feet, a number that could surpass 3000 feet over the next 10 years (Underwater, Sept. 2000).

Moreover, according to a study released at one of the world's foremost events for the development of offshore resources, the 2000 Offshore Technology Conference in Houston, oil companies will increase their spending on deep-water drilling by as much as 85 percent over the next five years (Associated Press, May 2000). Likewise, Underwater Magazine also reports, the numbers of subsea wells coming on line are expected to double from their 1999 peak by 2003, virtually quadrupling the installation rate since 1994 (Underwater, May 2000).

Even the term, deep-water, has taken on a new meaning as companies drill in deeper and deeper waters. Haliburton Subsea's deepwater group defines it as water depths greater than 500 meters, or 1640 feet. Oceaneering uses the term to mean water depths greater than 3000 feet. While 1000 ft was considered the deepwater standard for many years, the definition varies from company to company and industry-wide numbers as diverse as 1000 to 4000 feet are used (Underwater, March 2000). As the industry evolves will there even be need for further classification – ultra-deep water?

These factors, coupled with the high productivity of many of these deepwater fields are generating a frenzy for deeper developments. It was a similar progression to the "deepwater" of the '60s that served to renew a lagging interest in the Atmospheric diving suit, the result was the redesign of Joseph Peress' Tritonia – the product of which was the JIM suit and its future offspring.

Is today's deepwater push generating the same interest in the ADS as yesterday's?

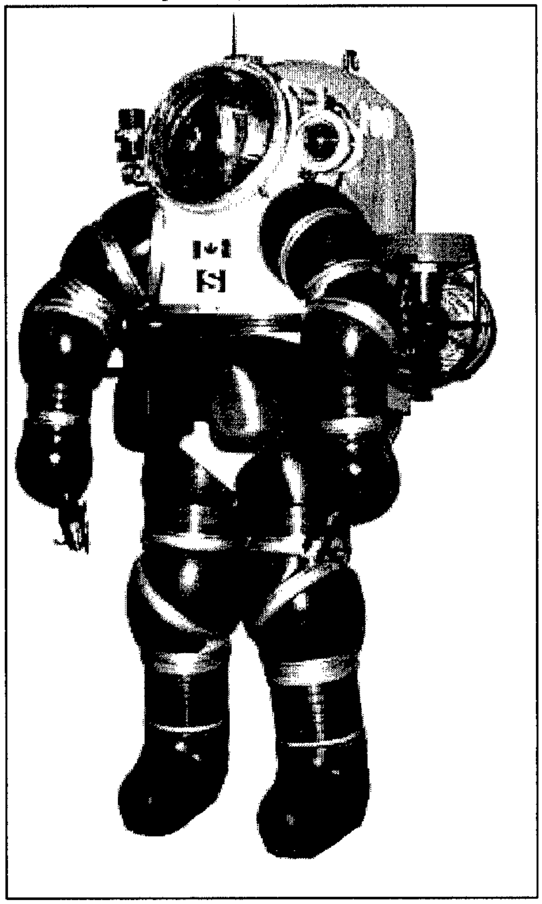
With the alternatives available to the offshore industry it won't likely result in revolutionary ADS technology, but it is likely to influence engineering decision-making. The Hardsuit 2000, currently used primarily by the Navy, has already been tested to 3000 FSW to Lloyds and ABS standards at Carderock Naval Surface Warfare Center in Maryland. "We think we can go to 3000 FSW without any redesign, whatsoever, and in fact they have been tested to that in a chamber, and theoretically we believe we can go as deep as 5000 FSW" says John Halwachs of Hardsuits, Inc. It was admitted that it would require a major redesign of the joints; and considering the engineering involved this is undoubtedly no small task. Atmospheric diving suits have already completed pipeline repairs in depths of greater than 2000 feet (Norman, 2000). The pipeline repair, completed at 2000 feet, was made to an 8-inch gas pipeline connecting a well in Mariner Energy's Pluto field to a platform 29 miles away. If the ADS, and specifically the joints, can be engineered to go deeper while still maintaining limb flexibility, there is no greater difficulty or risk of life at 5,000 ft as there is in 2,000 feet. Industry demand may ultimately decide the fate of the ADS, but it doesn't appear that their will ever be another 100 year gap in ADS technology. Likewise, with the French, U.S. and Italian Navies all owning ADSs, the technology seems to be well engrained into the Deep Submergence Rescue programs.

Next Generation

HARDSUIT 2000

More correctly 'present generation', the HARDSUIT 2000, already ocean-tested and fresh from a submarine rescue exercise in Singapore, is the latest development by Hardsuits International. Developed at the request of the U.S. Navy, the HARDSUIT 2000 is a forged aluminum 610 meter version of the shallower suits, designed to the Navy's stringent requirements. The U.S. Navy has taken delivery of one suit and three more are on order. The HARDSUIT has also been an integral part of both the French and Italian Navy Submarine Rescue Programs since 1993.

Figure 22: HARDSUIT 2000 (Courtesy of Hardsuits Incorporated).



Additionally, Hardsuits is exploring other avenues to update their ADS. Jim Halwachs, Hardsuits Engineer says that Hardsuits Inc. is currently doing prototype testing of Electric Ring Propulsors (ERP) such as those seen on the Quest ROV from ALSTOM Automation Schilling Robotics. Some of the obvious advantages of the ERP are less moving parts and therefore less wear and maintenance. The disadvantage is the initial cost, but if proven to be a reliable alternative to the standard motor-driven propeller, their could well be a long term cost savings. Likewise, various inspection

packages, such as cathodic protection inspection packages, are being added to their ADS to broaden their usefulness.

WASP® 3

The next generation WASP, of which two are expected to be produced in 2001, will be the first major update to the Oceaneering-owned atmospheric diving suit since the WASP was introduced. According to Eric Hammans, Oceaneering Project Manager, the new WASP will have three times more powerful thrusters, longer life support, updated atmospheric monitoring system, lateral thrust capability, two onboard camera systems, enhanced thruster control and fiber optic data transmission. Additionally, it will have and a updated and redesigned control room with computer readouts of all the essential functions. Departing from their traditional yellow WASP, the WASP® 3 will be an orange, 2500 feet version of the current WASP. The new thruster system will also be vectored in such a way to allow movement in the lateral direction, a feature not common on most atmospheric diving suits.

Figure 23: EXOSUIT, prototype atmospheric diving suit. (Courtesy of Nuytco Research Ltd.)

EXOSUIT

Dr. Phil Nuytten, inventor of the NEWTSUIT and considered by many as a pioneer in the atmospheric diving suit industry, has introduced what may be the future of atmospheric diving suits. The EXOSUIT promises to be a swimmable and non-tethered one-atmosphere diving suit. A full-scale mock-up at this year's Underwater Intervention conference in Houston resembled

the stuff only seen in science fiction movies. But this is not science fiction, Phil Nuytten has delivered before. When confronted with skepticism Dr. Nuytten commented "the same things were said about the NEWTSUIT before it went into production as I've heard about the EXOSUIT".

The two standout-features as underlined above are swimmable and non-tethered. Current atmospheric diving suits in use today are too heavy to facilitate manually propelling them, with the exception of walking, from one location to another. The EXOSUIT is expected to be light and flexible enough to allow just that. With 22 highly mobile rotary joints, Bob Evans designed swim fins, and an estimated final weight of 160 lbs. in air (minus the operator), its pilot may well be able to swim from site to site. The EXOSUIT will have a 48-hour life support and the latest in underwater communications. Non-tethered is, of course, sure to bother the most die-hard commercial divers, who have come to depend on the tether as a lifeline and for everything from compressed air to communications.

CHAPTER IV

METHODS OF UNDERWATER INTERVENTION

Diving Systems

Air Diving Systems

Self Contained Underwater Breathing Apparatus (SCUBA)

Figure 24: Scuba Diver (Courtesy of National Undersea Research Program)

The first workable, open-circuit demand-type self-contained underwater breathing apparatus, more commonly known as SCUBA, was developed in the 1940's by Jacque-Yves Cousteau and Emil Gagnan. The freedom SCUBA brought to the world at that time led to the development of diving as a sport. SCUBA affords the diver unparalleled mobility, freedom of movement and dexterity but is limited to very shallow depths. The generally accepted maximum for air diving is 130 FSW due to the limited breathing gas supply (Nuckols, 1996).

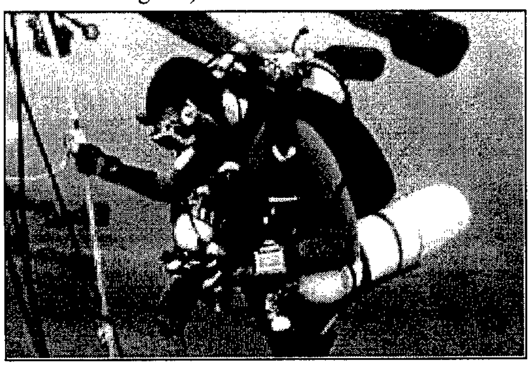
Surface Supplied Diving

Surface-supplied air divers usually have an unlimited source of air, supplied through an umbilical connected to the surface. As compared to SCUBA, the umbilical allows a

prolonged stay at the bottom, but also limits the upward/downward excursion distance and range around the dive site. Surface-supplied divers are limited to depths less than 190 feet due to the increasingly narcotic effect of nitrogen at greater pressures.

Mixed Gas Diving

Figure 25: Mixed gas Diver, decompressing from a dive to 190ft (Courtesy of National Undersea Research Program)

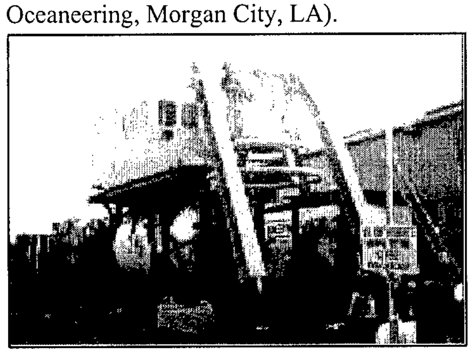


Mixed gas systems are meant to eliminate or reduce the physiological effects that are involved with standard air, by using specific mixtures of nitrogen and oxygen (nitrox), helium and oxygen (heliox) or oxygen-helium-nitrogen (trimix). Mixed gas systems are capable of much greater depths, up to 350 feet for certain mixtures, but suffer some of the same limitations as surface-supplied air diving due to the umbilical connection between the surface and diver.

Saturation Diving

The principle of saturation diving was advanced by Capt. George Bond, MC, US Navy and the *Sealab Program*. By completely "saturating" the divers bodies with gas at depth and allowing them to remain at depth throughout the mission (Mayberry, 2000). With the use of transfer capsules and decompression chambers divers could avoid accumulating decompression times and only decompress once at the end of the dive. Divers could remain under pressure for days, even weeks, before completing the

Figure 26: Saturation System (Courtesy of Oceaneering, Morgan City, LA).



mission. The divers are transported at pressure to the worksite by a personnel transfer capsule (PTC), exit the PTC at depth to perform work, and return to the surface via the PTC to live in a pressurized deck decompression chamber (DDC) aboard a support vessel. This scenario is completed as many times as necessary till the mission is complete, when the divers will decompress inside the DDC. The general rule of thumb for decompression is one day per 100 feet of depth plus one day. Using this rule of thumb for the offshore industry's accepted maximum of 1000 feet, each saturation diver would require a minimum of 11 days of costly but non-productive decompression time. Additionally, to pressurize divers to 1,000 ft it can take as much as 24 hours. Another disadvantage of saturation divers is that they have a very limited up and down excursion range from their PTC.

Atmospheric diving suits

See Chapter III for a description of the modern atmospheric diving suit, its advantages, and disadvantages.

General Diving

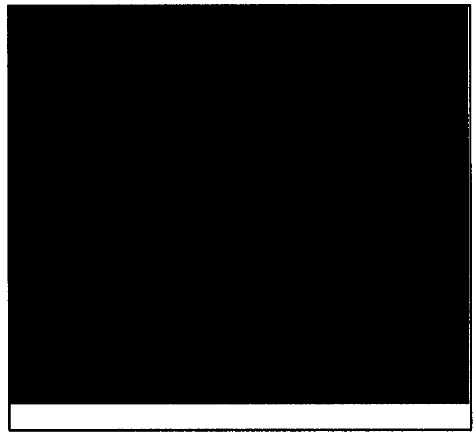
Good divers in general are highly-trained specialist with sometimes unusual physical and psychological characteristics, but the best still can't dive to 2000 feet, spend two to four hours on the job, and return to the surface as if it were 20 feet. Additionally, the Center for Disease Control and Prevention in Atlanta reported in June of 1998 that commercial divers are 40 times more likely to die or have a major accident than any other workers are (Hays, 2000).

Underwater Vehicles

Manned submersible

Most manned submersibles will allow the operator to depths not obtainable by any other means of manned underwater intervention. This, allows the operator to have first hand knowledge of the deep environment. The operator, though, is still isolated from the environment with the exception of his sight. Submersibles are also generally large and cumbersome vehicles, preventing any useful work in tight or enclosed spaces. But they are getting smaller, an example is Nuytco's latest creation the one-man Deep Worker submersible. With a length of 8.25 feet, beam of 5.3 feet, height of only 4.5 feet, and optional hydraulic manipulators, the Deep Worker has the potential to do real work in the sometimes close confines of the underwater world. Deep Worker is also rated to 2000 feet, has a payload of 250 lbs., can travel at 3 knots, and has an onboard life support of 80 hours (Nuytten, 1997).

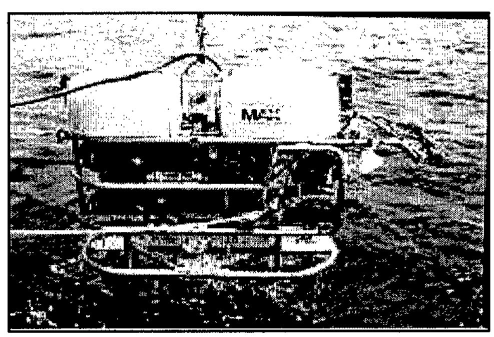
Figure 27: Nuytco Research Ltd. Deep Worker.



Unmanned Underwater Vehicle (UUV)

<u>Remotely Operated Vehicle (ROV)</u>

Figure 28: Max Rover ROV (Courtesy of National Undersea Research Program)



Remotely operated vehicles, or ROVs, completely eliminate the human risk factor underwater, but presents the most isolation from the project site and generally requires very adept operators to achieve tasks easily accomplished by divers. ROVs have evolved from simple unreliable "eyeballs" used in research and military arenas to useful tools in the offshore oil and gas industry. They typically require very little personnel support as compared to other means of underwater intervention. Work class ROVs can now operate at depths of up to 10,000 feet and

research ROVs have reached the deepest points of the Marianas Trench, at 36,000 feet (Westwood, 2000).

Autonomous Underwater Vehicle (AUV)

Figure 29: NOAA AUV Odyssey being deployed (Courtesy of National Undersea Research Program).

Autonomous underwater vehicles, or AUVs, the newest method of underwater intervention, are essentially robots designed to carry out specifically programmed automated tasks, such as deepwater seabed survey or oceanographic data collection, with little to no real-time communication to the surface necessary. The AUV, is a technology that is not yet fully mature, but with development over the next several years, is poised to make quite an impact on the offshore oil and gas industry - to the tune of $100 million dollars. That's the figure Shell expects to save over the next five-years, with the use of the AUV in the exploration and production industry (van der Veen, 2000). AUVs currently can conduct little to no real underwater intervention and are presently 'observation' vehicles, but not in the traditional sense.

Comparison of Specific Underwater Intervention Methods

Selection of any work package alternative usually equates to 'fitness for purpose', or selection of the most fit solution, logistically, economically, and operationally to meet the purpose at hand, i.e. the demands of the mission. Table 1 is an economic and capabilities comparison of Saturation Diving, ROVs and atmospheric diving suits based on a recent cost study done by Hardsuits International.

Table 1: Cost and capability comparison of portable saturation system, remotely operated vehicle, and atmospheric diving suit for a 24 hour operation/1000 feet dive (Courtesy of Hardsuits International).

SATURATION SYSTEM, ROV, ADS COMPARISON
(1000 feet – 24 hour operations)

SPECIFICATIONS/COSTS	**SATURATION**	**ROV**	**ADS**[1]
Depth Rating	300 – 1000 feet	10,000 feet	0 to 1200 feet[2]
Equipment Capital Cost	$6,000,000.00	$4,200,000.00	$3,500,000.00
Equipment Weight	100 tons	72.6 tons	60.4 tons
Deck Space Requirements	2045 ft^2	750 ft^2	860 ft^2 [3]
Daily Equipment Charge	$5,500.00	$2,100.00	$5,910.00
Daily Personnel Charge	Crew of 22 @ $12,840.00	Crew of 06 @ $4,650.00	Crew of 12 @ $6156.00
Daily Dive Bonus	$2,220.00	N/A	$1,620.00
Daily Gas and Consumables	$2,100.00	$400.00	350.00
Desat (Decompression)	$249,260.00[4]	N/A	N/A
Total Daily Cost - less Desat	$22,660.00	$7,150.00	$14,036.00
CAPABILITY/LIMITATIONS			
Human Risk Factor	Moderate	N/A	Very Low
Pre- Job Engineering	Very Low	High	Low
Structure/Task Access	Limited by position of bell & umbilical, 150 ft	Limited by size of vehicle & tether, 660 ft	Limited to 1800 ft of tether
Work Site Feedback	Camera, Hardwire communications through helium unscrambler	Camera	Camera, digital communications, through water communications
Visibility/ Sensors	Human eye, camera, compass, and touch	Camera, sonar, and compass	Human eye, camera, sonar, compass, and limited touch
Depth Excursions	Limited to upward and downward saturation excursion tables	Unlimited	Unlimited
Unscheduled Tasks	Very adaptable, within depth excursion table limits	Task dependent	Very adaptable
Tooling	Normal hand and power tools	Special purpose tooling	Amended hand and power tools

Notes:
(1) ADS values are based on data from Hardsuits International, but for comparative purposes is applicable to Oceaneering's WASP.
(2) Based on the HARDSUIT 1200. The WASP is rated to 700 meters and the commercial version of the U.S. Navy's HARDSUIT 2000, to be designated the HARDSUIT 2500, is rated to 760 meters (2500 FSW).
(3) Two ADSs and two Launch and Recovery Systems are deployed on each job; one is in standby while the other is at work.
(4) Desat crew and equipment @ 22,660.00 per day for 11 days of decompression.

From Table 1, it's not readily apparent which system will best suit the task at hand, but it can serve as a decision making tool when weighing the cost and capabilities against the mission requirements.

Operational Factors Affecting Intervention Modes

Table 2, on the following page, lists some operational concerns that should be answered when selecting a method of underwater intervention. In most cases the same factors involved in pre-project planning for any job relate as well to the selection of an underwater intervention method. The list is not meant to be all-inclusive and every job may be unique in its requirements.

Table 2: Considerations in the selection of underwater intervention methods.

Depth(s)	What is the maximum depth at the work-site?
	Are large excursions necessary up and down the water column?
	If the water depth is within diving range then either ROV, ADS or ambient diver may be acceptable.
Safety/Risks	Is there an inherent risk to life or property?
	Can the risks be reduced with safety factors, pre-engineering, or redundancy?
	Manned intervention, whether ADS or diver, especially requires a great deal of emphasis on safety. Property can be replaced, people can't.
Type of task	Does the task require fine or gross manipulation of tools or devices?
	Is it an observation only task?
	ROVs are well suited to observation-only tasks, especially of long duration, but separate the human brain, eyes and hand from the work-site. Divers can obviously provide the most dexterity on site, ADS next, and ROVs last.
Task Difficulty	Are large applications of forces required?
	Does the work site have good accessibility?
	Divers and ADSs are very limited in physical payload, but can usually access tighter spaces than the ROV and still accomplish real work.
Mission Duration	Does the mission require long stay times at the work-site with little opportunity for mission breaks?
	With no physiological restraints the ROV generally has a longer stay time.
Operator Experience	Are your operators experienced at the particular task?
	Operator experience at the task may play a significant factor in selecting the intervention method. In other words, a very experienced ROV operator with specific experience at the task at hand may be able to complete it faster than an ADS operator with limited experience. When common sense usually dictates that the ADS will be faster than the ROV. Note that many shortcomings in experience may be overcome with pre-dive training.
Available Support	What equipment/personnel are already on site or immediately deployable?
	Eliminating mobilization of crew and equipment will generally get the job completed faster.
Productivity	How time-efficient is the method of intervention in completing the particular task?
	As previously stated, generally the diver is the most time-efficient means to complete most tasks, secondly the ADS, and thirdly the ROV.
Economic Factors	What is the cost in terms of dollars?
	What is the cost in terms of time?
	A significant cost can be incurred just in terms of time and at the current price of oil a barrel at about $30.00 (OPEC Monthly Oil Market Report, July 2000), with often many thousands of barrels per hour at stake till a repair job is completed, hundreds of thousands of dollars in capital is at risk.
Mobilization/ Demobilization Time	Mobilization and demobilization time certainly adds to cost and can additionally delay a short-fused requirement.
Special Considerations	Back up: Most ADS operators require a back up ADS for safety.
	Method Engineering: If the selected intervention method cannot perform the specific task, can the task be tailored so that it may be done by the selected system? Will the selection of intervention require specially designed tools or operating devices to complete the job? ROVs have a very limited ability to improvise, thus pre-engineering of methods and tools become very critical.

As with jobs above the water line, irrelevant of which 'tool' or method is selected to complete the job, an accurate description of the task and some good pre-job planning will significantly factor in the success of the project (Peterson, 1998).

Proposal for a comparison of underwater intervention methods

In order to completely compare underwater intervention methods a series of experiments could be devised such that each individual method of underwater intervention is required to perform the same task at the same depth. The task would be a dexterity task that can be accomplished by all methods of underwater intervention and the task depth would be constrained to the most depth-limited method, i.e. Scuba.

Since, most other elements of time-cost are fixed, the dexterity task would give a relative efficiency of each method for a like task. Elements compared that are not directly related to the dexterity task should be:

- Mobilization Time

- Preparation Time, or variable mobilization time, in units of time per foot of depth, this is especially important in saturation diving where divers are compressed to depth prior to diving.

- Time to get from the surface to the underwater worksite, in minutes per foot of depth.

- Time to complete the job. An "efficiency factor" could then be generated for each underwater intervention method.

- Time to return to surface, in minutes per foot of depth.

- Surface decompression (and/or post-dive operations)

- Demobilization Time, fixed and variable

It is of course obvious that some real world tasks are not performable by some methods of underwater intervention, nor is it practical to use every method that could perform some tasks. Additionally, a specific dexterity task may not equate well to other underwater task. For instance there may be a specific task performed more easily by the ADS than the ROV, but other tasks where the reverse is true. But for most underwater tasks the completion time would likely relate very closely to the dexterity of the intervention device itself.

CHAPTER V

ROLE OF ATMOSPHERIC DIVING SUITS IN THE NAVIES

U.S. Navy – Deep Submergence Rescue

JIM

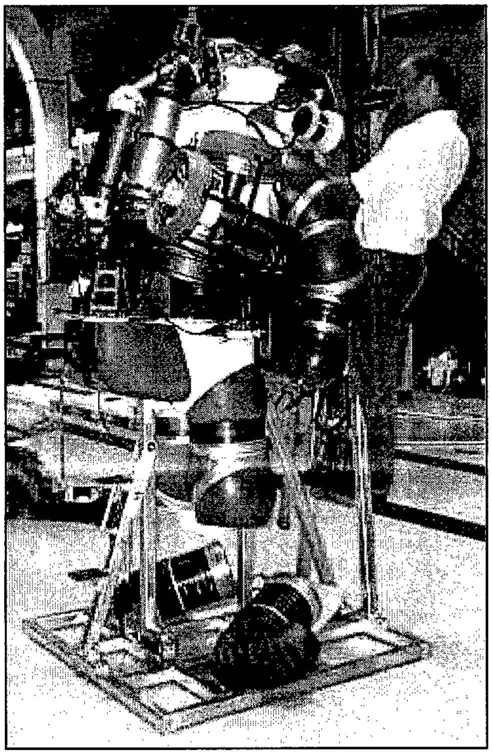
The U.S. Navy first researched the atmospheric diving suit in the 1970's. Under a joint trial the Royal Navy's Physiological Laboratory and U.S. Navy's Medical Research Center both conducted tests on the newly developed JIM suit and shared their information (Carter, 1976). The tests were conducted over a two-week period in June 1975 at the Navy Experimental Dive Unit in Panama City, FL. JIM was determined to be a viable underwater tool, but ultimately the Navy decided against employing the JIM suit on the basis it could not be certified to Navy standards. This was due to the inability to ensure integrity of its non-metallic composite hull over a given system life.

NEWTSUIT

Following the JIM suit, the U.S. Navy's Coastal Systems Station (CSS) in Panama City, FL in the early 1990's evaluated the NEWTSUIT. It was determined the NEWTSUIT had good operational capability, but again their were problems with the cast aluminum hull satisfying Navy certification standards to the desired operating depths. At the request of CSS, Hardsuits Inc. replaced the cast aluminum hull with higher strength forged aluminum resulting in the HARDSUIT.

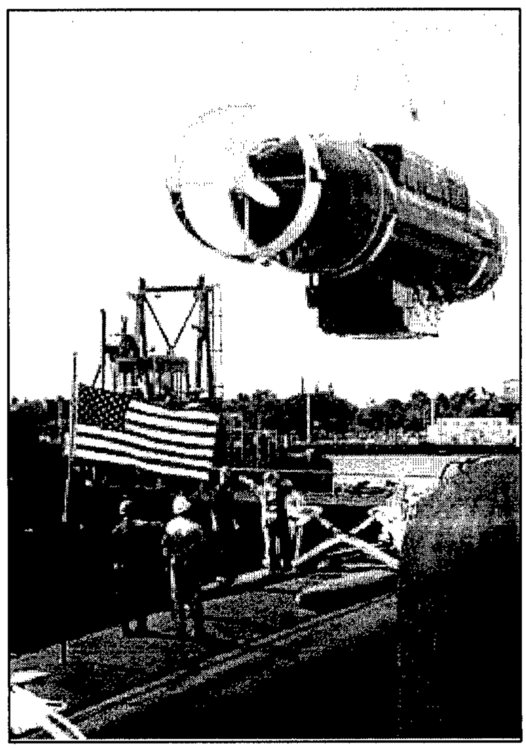
HARDSUIT 2000

Figure 30: Engineer inspecting HARDSUIT 2000 at Navy Experimental Dive Unit (US Navy Photo)



The latest addition to the Navy's suite of Submarine Rescue equipment is the HARDSUIT 2000 (Figure 30). The HARDSUIT 2000 can dive as deep as 2000 feet for many hours without any of the physiological hazards of depth, such as the "bends" or nitrogen narcosis. Developed by Hardsuits Incorporated (Vancouver, British Columbia, Canada) at the request of the Navy, the HARDSUIT 2000 is currently undergoing pier-side testing with the Deep Submergence Unit's (DSU) Diving System Support Detachment (DSSD). The suit is expected to complete open ocean dives in time for an international exercise in the fall of 2000.

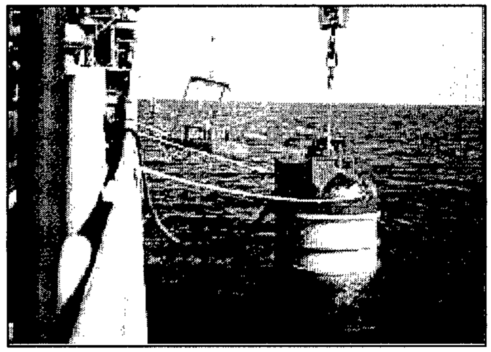
Figure 31: DSRV 2 Avalon is lowered down onto the top of USS Greeneville (SSN 772) for a submarine rescue exercise (US Navy Photo).



The DSU also operates the U.S. Navy's Deep Submergence Rescue Vehicles (DSRV), as seen in Figure 30. The Mystic (DSRV-1) and Avalon (DSRV-2), were

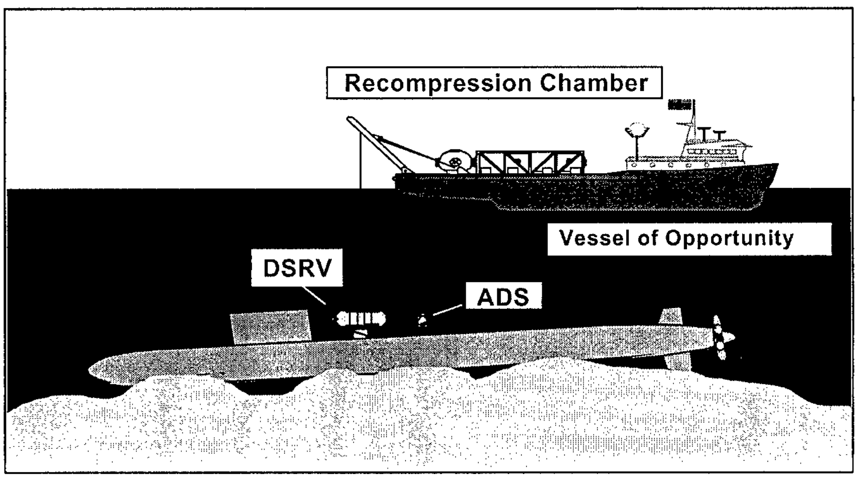
completed in 1971/1972. They have a max rescue depth of 2000 feet, hence the relationship with the HARDSUIT 2000. The Avalon was decommissioned in August 2000, reducing the Navy's DSRV fleet to one (McMichael, 2000). Coincidentally, much to the chagrin of submarine rescue advocates, this occurred soon after the Russian submarine Kursk's accident.

Figure 32: Submarine rescue chamber being lowered from a rescue ship (US Navy Photo).



The basic concept of operation is similar to that of the divers involved in the rescue of the *USS Squalus* (SS-192) in 1939. Once a disabled submarine (DISSUB) has been located, the HARDSUIT 2000 could be deployed to the site within hours and begin conducting an initial survey of the submarine while providing the rescue team with video, sonar and personal observations (Sadorf, 1999). The primary task of the HARDSUIT 2000 would be to clear debris from the submarine hatch, remove the hatch fairing and connect the down-haul cable from the submarine rescue chamber (SRC), a successor to the McCann Rescue Bell, to the submarines hatch. The opposite end of the cable is fed to a winch in the lower compartment of the SRC. The slightly positively buoyant SRC will then winch itself down to the DISSUB hatch.

Figure 33: Concept of operations scenario with DSRV, ADS and Vessel of Opportunity. (Courtesy of US Navy).



After the SRC is drawn tight to the DISSUB by the winch, the lower compartment of the SRC is pumped dry and reduced in pressure to produce a watertight seal around the hatch. The SRC would then be able to transport six submariners to the surface at a time by paying out the winch cable till the SRC has reached the surface. The SRC, a light-weight four point mooring system, a 300-HP rigid-hull inflatable boat, and all support equipment could easily be loaded onto a C-5 cargo plane at North Island Naval Air Station San Diego, CA, and transported anywhere in the world within 48 hours. Additionally, the HARDSUIT 2000 could be used to deliver emergency supply pods and assist locking them into the sub. Emergency supply pods would contain life-sustaining consumables, such as food, medicines, and carbon dioxide absorbent, to be used by the confined submariners. Following these primary tasks, the HARDSUIT 2000 could continue to provide support and observations on-site to further assist the rescue efforts. Secondary missions for the HARDSUIT include salvage and deep-ocean recovery. Currently the Navy has taken delivery of one HARDSUIT 2000 and its accompanying launch and recovery system (LARS) and is awaiting three more units and an additional LARS following satisfactory certification of the first suit.

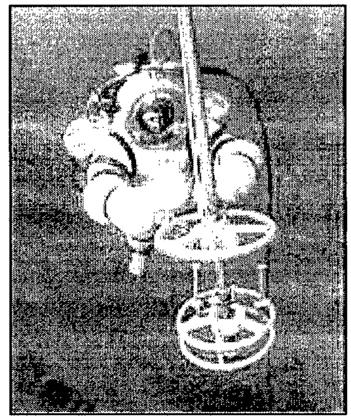
Much like the submarine community would conduct sea trials of new submarines, CDR Kurt Sadorf of DSU, North Island says, "the DSU is in the initial test phase of the HARDSUIT 2000". DSU has most recently conducted pier-side tests of the HS2000 in San Diego. After the shallow-water test the suits were brought up and underwent a complete structural integrity check. DSU will also soon be conducting open-water testing to the rated depth off the coast of California and plan to participate in a multi-national submarine rescue exercise in late September/October off Singapore.

French Navy

According to a Hardsuits Inc. activity summary the French Navy has been closely involved with the HARDSUIT 1000 since 1992. The French Navy currently has one

HARDSUIT 1000 in service and a team of five trained pilots (Corizeau, 1999). The HARDSUIT will make the first on-site damage assessment and may attach air hoses capable of replenishing air and depressurizing the submarine.

Figure 34: French Navy Newtsuit installing submarine air hoses in a submarine rescue



In case of a French submarine accident, the Intervention Sous la Mer Unit (Undersea Intervention Unit) in Toulon receives the alert and either the *Aqueyron*, a French Navy rescue vessel, or an aircraft would bring in the HARDSUIT 1000 team. For such submarine rescue operations, the U.S. could also use its DSRVs. These DSRVs can dive down to 2000 feet, can be carried "piggy-back" on any U.S., French, and other submarines, attach to a damaged submarine and evacuate up to 24 submariners at a time.

Italian Navy

The Italian Navy has developed their ADS program over the last seven years and currently own three HARDSUIT 1000s. Their suits are used for submarine rescue and deep-diving activities including interface to the McCann rescue chamber, air-hose attachment, and marine salvage.

CHAPTER VI

DESIGN CONSIDERATIONS OF THE ATMOSPHERIC DIVING SUIT

Introduction

Objective

The objective of this chapter is to design a lightweight low-volume atmospheric diving suit capable of reaching depths of 3000 feet and suitable for scientific, industrial and military applications. A design depth of 3000 feet was chosen to completely exceed all current ADS depth capabilities. The present WASP is rated to 2300 feet with two improved versions expected operational in 2001 to be rated to 2500 feet. The commercial version of the HARDSUIT 2000, due to the differences in commercial and U.S. Navy certification criteria, will be rated to 2500 feet.

Design Criteria

The design criteria are that it has to be capable of diving to 3000 feet, with or without an umbilical. The suit itself must be lightweight in order to simplify buoyancy compensation. It must be capable of a sustained mission time of 12 hours. It must have good corrosive characteristics in seawater. It must be low-volume, i.e. have a low aspect ratio, in order to reduce drag. It must be streamlined, as much as feasible, to decrease skin-friction drag. Additionally, the suit must have adequate controls to minimize the danger to life in an emergency situation. In all cases, where possible, the American Bureau of Shipping (ABS) Rules for Building and Classing Underwater Systems and Vehicles (1979) is used as a guideline for designing this suit.

Pressure Vessel Design

The pressure vessel itself was designed to accommodate the 5th to 95th percentile athletic male and 50th to 95th percentile athletic female based on anthropometric measurements obtained from *Anthropometric Methods: Designing to Fit the Human Body* (Roebuck, 1995). Extensions, in the arms and legs, of the pressure vessel may be added to accommodate operators outside these ranges. All individual elements of the pressure suit were modeled as simple geometric shapes. The arms, legs, torso and feet were modeled as hollow cylinders, while the head, shoulders, pelvis, elbows, hands, knees and ankles were modeled as hollow spheres or hemispheres as applicable. Reviewing the previous pictures of past and current suits it can be observed this is not an unrealistic assumption. As important as typical anatomical dimensions of length and circumference are in designing the components, dimensions such as the diameter around the elbow of the arm when the arm is bent at maximum allowable flexion is also significant. This dimension determines the minimum diameter of the elbow joint in rotary-jointed atmospheric diving suits (Fonda-Bonardi, 1967).

General Equations

Allowable External Pressure for stiffened (or un-stiffened) hollow cylinders is given as (Rules for Building and Classing Underwater Systems and Vehicles, 1979):

$$P = \frac{2.42E(t/2R)^{5/2}}{1.5(1-v^2)^{3/4}(L/2R - 0.45\sqrt{t/2R})} \qquad \text{[psi]}$$

where E is Young's modulus, v is Poisson's ratio, t is the shell thickness, L is the length of the cylinder, and R is the mean radius of the shell.

For the spherical elements, the maximum allowable working pressure, again using ABS standards, was based on the lower of P_1 and P_2 determined from the following equations:

$$P_1 = \frac{\sigma_y C}{0.75} \text{ [psi]} \qquad \underline{\text{or}} \qquad P_2 = \frac{0.92EC^2}{\sqrt{3(1-\nu^2)}} \text{ [psi]}$$

where σ_y is the Yield strength and *C* is a factor given from Figure 9.2 of the ABS Rules.

All components were designed for an external pressure of 1.25 times the rated depth of 3000 FSW, or ~1690 psi, per ABS standards for initial hydrostatic testing. Additionally, the minimum factor of safety for all components was 2.3, for a nominal thickness of 0.3 in. Considering the risk to life, in the event of a catastrophic failure of any component, this was deemed an appropriate factor of safety. Most factor of safety's were higher, but thicknesses were kept constant at 0.3 in for ease of manufacture and assembly. A spreadsheet of all pressure vessel design dimensions and calculations is included in Appendix A.

Joints

The most significant piece of the engineering puzzle is the design of the joint. The component pressure vessels would be joined together by pressure-balanced oil-filled rotary joints, such as on the Hardsuit family of ADSs, or segmented oil-filled ball-and-socket types joints, like the WASP joints. The joint design has been neglected in this discussion.

Material Selection

Titanium was chosen for the pressure suit material for its excellent strength and corrosion resistance, and low specific weight. The head hemisphere is to be constructed of an optical grade polycarbonate material. According to a U.S. Geological Survey publication, *Metal Prices in the United States through 1998*, raw titanium costs approximately 4.5 dollars per pound, as compared to aluminum, which is about 0.65 dollars per pound. Glass reinforced plastic costs are highly variable depending on

design and fabrication difficulty. See Appendix B for a look at how the individual suit components are assembled.

Buoyancy

Suit weight was kept as low as possible to allow flexibility in ballasting for neutral buoyancy. Space within the suit would be allowed to add internal ballast without adding buoyancy. Two cubic feet of syntactic foam (AM-32) would serve as a means of controlling the center of buoyancy and additionally on critical areas as a protective 'bumper' for the suit and finish. In this design (Table 2) a 175-lb operator would require 29 lb of internal ballast to create a slightly positively buoyant suit (+1.0 lb). Therefore, just 2.5 lb of jettisonable ballast (neglecting its buoyancy) would make the suit slightly negative. A low negative buoyancy allows the operator to walk along the bottom more easily without sinking into the surface. Jettisoning ballast in an emergency would give the suit a 1.5-lb upthrust, creating a slow and controlled ascent to the surface. Since, the suit is not an expanding volume, the rise-rate remains constant. Experimental results by the U.S. Navy indicated typical rise-rates for the JIM suit approached 100 feet per minute upon jettisoning its external ballast (Matzen, 1980).

Normal and Emergency Life Support

Determination of Metabolic Load

The rate at which carbon dioxide ($\dot{V}_{CO_2}$) is being produced is directly related to the oxygen consumption rate ($\dot{V}_{O_2}$) and the respiratory quotient (RQ). From Figure 6, moderate work level is 1 *l*/min and RQ is 0.9.

$$\dot{V}_{CO_2} = \dot{V}_{O_2} \cdot RQ$$

The metabolic load ($\dot{m}_{CO_2}$) for the scrubber is defined as the mass generation rate of carbon dioxide during the mission, given in pounds of carbon dioxide per hour. This metabolic load can be found by multiplying the carbon dioxide generation rate ($\dot{V}_{CO_2}$) by the density of carbon dioxide (ρ_{CO_2}) at conditions of $32^\circ F$ and 1.0 Atm.

The metabolic load ($\dot{m}_{CO_2}\ ^{lb}\!/_{hr}$) for the scrubber is then calculated as such:

$$\dot{m}_{CO_2}\ ^{lb}\!/_{hr} = \frac{\dot{V}_{CO_2}\ ^{l}\!/_{\min}}{28.3\ ^{l}\!/_{ft^3}} \cdot \rho_{CO_2}\ ^{lb}\!/_{ft^3} \cdot 60\ ^{\min}\!/_{hr}$$

Calculation of Breathing Gas Mixture

Weight of CO_2 produced during 12 hour (or 84 hour) mission, is simply;

$$\text{Weight of } CO_2 = \text{Metabolic Load } CO_2 \cdot \text{Mission Period}$$

Volume of O_2 that must be to replaced during a 12 hour (or 84 hour) mission;

$$\text{Volume of } O_2 = \text{Weight of } O_2 \cdot \text{density of } O_2$$

Calculation of Pure O_2 Supply Container Pressure

Pressure of the O_2 supply container may then be found using Boyle's Law and an appropriate safety factor:

$$P_1V_1 = P_2V_2$$

Calculation of Theoretical Absorption Capacity

Chemical formula for lithium hydroxide;

$$2LiOH + CO_2 \Rightarrow Li_2CO_3 + H_2O$$

Theoretical absorption capacity of lithium hydroxide, is then;

$$\text{Theoretical Absorption Capacity} = \frac{\text{Moles CO}_2}{\text{Moles Absorbent}} \cdot \frac{\text{Molecular Wt. CO}_2}{\text{Molecular Wt. Absorbent}}$$

Calculation of Canister size for CO_2 Scrubber

$$\text{Mass of LiOH required} = \frac{\text{Metabolic Load}}{\text{Theoretical Absorbtion Capacity}} \cdot \frac{\text{Mission Time}}{\text{Scrubber Efficiency}}$$

$$\text{Scrubber Efficency } (\eta) = 0.5 \text{ to } 0.8$$

Internal Design Volume:

$$\text{Volume of Canister } = \frac{\text{Mass of LiOH}}{\text{Density of LiOH}}$$

Environmental Controls

Dehumidification Requirements

Moisture produced by breathing gas operations may be calculated as follows:

$$\text{Water Production Rate} = \frac{\text{Moles H}_2\text{O}}{\text{Moles CO}_2} \cdot \frac{\text{Mol Wt H}_2\text{O}}{\text{Mol Wt CO}_2}$$

$$\text{Water Produced} = \text{Water Production Rate} \cdot \text{Mission Time}$$

Based on the previous calculations a commercially available dehumidification agent, such as Damp Rid® may be necessary component of the interior of the suit. Damp Rid® can eliminate 1lb moisture per 1 lb of agent.

Heat Transfer Considerations

Through suit heat transfer

The rate of heat transfer, in Btu/hr and kW, is also given in Table 2. The heat transfer coefficient for Titanium is given as approximately 3.83 Btu/hr-ft-F (Beer, 1992). This yielded nearly 50kW of heat required to keep the suit at a comfortable level for the operator, therefore a thin layer of insulation (0.25") was added to the inside of the suit. Adequate space was allowed during the design process for the installation of insulation if necessary. Using a typical value of thermal conductivity for insulation (k_{ins}) of 0.02 Btu/hr-ft-F, the heat transfer was reduced to less than 4 kW of heat transferred. Therefore, no additional heating of the suit is necessary.

Heat transfer caused by CO_2 Scrubber

$$\text{Heat Produced} = \text{Theorectical Heat of Absorption} \cdot \text{CO}_2 \text{ Produced}$$

$$\text{Heat Produced} = \frac{875\ \text{Btu}}{\text{lbm CO}_2} \frac{0.23\ \text{lbm CO}_2}{1\ \text{hr}} = 201.25 \frac{\text{Btu}}{\text{hr}}$$

This was considered an insignificant amount of heat.

Gas Supply Storage

Calculations for O_2 Pressure vessel

Wall thickness for pressure vessel:

Pressure at depth:

$$\text{Design Pressure} = \frac{(\text{Depth} + 33.1)ft}{33.1ft} atm \cdot 14.7\frac{psi}{atm} \cdot 110\% \text{ Safety factor}$$

If the internal pressure is over twice external pressure as calculated previously, internal pressure calculations only are required.

Cylinder portion:

Radius of cylinder is assumed to be 6 in, this fits snugly into the backpack.

Joint efficiency is assumed to be 1 for fully radiograph tested butt joints.

Stress value of material for SA 515 Grade 70 = $17500\, lb/in^2$ @ - 20 to 650 $°F$

$$\text{Wall thickness} = \frac{\text{Design Pressure} \cdot \text{Radius of Cylinder}}{(\text{Material Stress Value} \cdot \text{Joint Efficiency}) - (0.6 \cdot \text{Pressure})}$$

Maximum Allowable Working Pressure Confirmation:

$$\text{Maximum Allowable Pressure} = \frac{\text{Stress Value of Material} \cdot \text{Joint Efficiency} \cdot \text{Wall Thickness}}{\text{Radius of Cylinder} + (0.6 \cdot \text{Thickness of Wall})}$$

Spherical portion:

$$\text{Wall thickness} = \frac{\text{Design Pressure} \cdot \text{Radius of Cylinder/Sphere}}{(2 \cdot \text{Material Stress Value} \cdot \text{Joint Efficiency}) - (0.2 \cdot \text{Design Pressure})}$$

Maximum Allowable Working Pressure Confirmation:

$$\text{Maximum Allowable Pressure} = \frac{2 \cdot \text{Stress Value of Material} \cdot \text{Joint Efficiency} \cdot \text{Wall Thickness}}{\text{Radius of Cylinder/Sphere} + (0.2 \cdot \text{Thickness of Wall})}$$

Canister Dimensions:

Height Calculations:

Internal design volume has been set at $1 ft^3$

$$\text{Volume of Canister} = 2 \cdot \text{Volume of Hemisphere ends} + \text{Volume of Cylinder}$$

$$= 2 \cdot \left(\frac{4}{3}\pi r^3\right) + \pi \cdot r^2 h$$

$$\text{Height} = \frac{\text{Volume of Canister} - 2 \cdot \left(\frac{4}{3}\pi r^3\right)}{\pi \cdot r^2}$$

The results of the life support design calculations are given on the following page.

Life Support Design Calculations

Given:

Oxygen consumption rate ($\dot{V}_{O_2}$)[1]	=	1.0 l/min	Depth	=	3000 ft
Respiratory Quotient (RQ)[2]	=	0.9	Mission Period	=	12 hr
Temperature	=	32.0 degrees F	Emergency Period	=	72 hr
Cylinder radius	=	5.0 in	Volume of supply container	=	1 ft^3
Joint Efficiency[4]	=	1.0	Scrubber Efficiency (h)[3]	=	0.5
Molecular Wt H_2O	=	18.0 lbm	Material Stress (SA515 Grade 70)	=	17500 lb/in^2
Molecular Wt CO_2	=	44.0 lbm	Density of O2	=	0.088 lb/ft^3
Molecular Wt LiOH	=	23.9 lbm	Safety Factor	=	110 %
R_{CO2}	=	35.11 ft-lbf/lb-R	Density of LiOH	=	28.0 lb/ft^3

Solutions: Metabolic Load

CO_2 production rate $(\dot{V}_{CO_2})$ = 1 * 0.9 = 0.9 l/min

Density of CO_2 @ 32F and 1 atm = 0.120581 lb/ft^3

Metabolic load $(\dot{m}_{CO_2} \, {}^{lb}\!/_{hr})$ = 0.230 lb/hr

Calculations for Breathing Gas Mixture (84 hour; standard + emergency mission time)

Weight of CO_2 = Metabolic Load CO_2 * Mission Period = 19.33 lb

Volume of O_2 = Weight of O_2 / density of O_2 = 220.18 ft3

Pressure of the O_2 Supply Container

P_1 = 1atm V_1 = 1 ft3 V_2 = 220.2 ft3

$P_1V_1 = P_2V_2$ => P_2 = 3237 * 110% = 3560.25 ~ 3600 psi

Theoretical Absorption Capacity

$$2LiOH + CO_2 \Rightarrow Li_2CO_3 + H_2O$$

Theoretical Absorption Capacity = 0.92

CO_2 Canister Size

Mass of LiOH required = 42 lbm LiOH

Volume of LiOH Canister = 1.5 ft3

Dehumidification Requirements

Water Production Rate = 1.13 lbm H_2O (for a 12 hr standard mission time)

Gas Supply Storage

Pressure at depth = 1482 psi ~ 1500 psi

Since external pressure is over twice external pressure, internal pressure calculations only are required

Cylindrical portion:

Wall thickness = 1.173 in

Maximum Allowable Pressure confirmation = 3600 psi □

Spherical portion:

Wall thickness = 0.525 in

Maximum Allowable Pressure confirmation = 3600 psi □

Dimensions:

Volume of canister = 2*Volume of Hemispheres + Volume of Cylinder

$$\text{Volume of canister} = 2\cdot\left(\frac{4}{3}\pi r^3\right) + \pi\cdot r^2 h \quad \Rightarrow \quad \text{height} = \frac{\text{Volume of Canister} - 2\cdot\left(\frac{4}{3}\pi r^3\right)}{\pi\cdot r^2}$$

height = 8.67 in ~ 9 in

Therefore, overall dimensions of the cylinder are: height of 19 inches and a radius of 5 inches.

Notes:
1. Oxygen consumption rate for a moderate work level, from Figure 6.
2. Typical respiratory quotient ranges from 0.7 – 1.0.
3. Scrubber efficiencies ranges from 0.5 – 0.8.
4. Joint efficiency for a fully radiographed joint is assumed to be 1.0

Escape/Safety

Since the mechanics of getting in and out of the suit prohibit an escape free-of-the-suit, this section looks at ways to make the suit safer in all operations, and in the event of an accident to maximize the pilot's chances of survival, while rescue efforts are underway.

Jettisonable external ballast was added to the suit to make the suit just negatively buoyant. In the event of an emergency the ballast could be jettisoned from within the suit, making the suit positively buoyant. This ballast could also be designed to jettison automatically if the suit dropped below its design working depth. As a last resort, specific external packages could also be jettisoned, such as the thruster package.

Emergency Life Support gas would be accessed by a simple mouthpiece demand regulator just forward of the operators face. In event of flooding or other applicable emergencies, an operator simply tilts the head forward and breathes through the regulator. This eliminates the need for a cumbersome and uncomfortable permanent oral-nasal mask attached to the pilot. After 12 hours unless manually overridden the emergency gas would automatically flow at 1/4 standard liters per minute, the normal oxygen consumption rate for a sedentary person.

An *Acoustic Pinger and Strobe Beacon* is attached that can be operated by the pilot, or in event of unconsciousness self-activates after the normal mission time of 12 hours.

Operational procedures such as operating the suits only in pairs would provide an additional measure of safety.

Additional Considerations

Umbilical design and drag considerations, while beyond the scope of this report, is a factor that would have to be further studied. This drag induced by the tether is the main reason for the introduction of the tether-management-system in the Remotely Operated Vehicle community.

Communications is a vital necessity for most underwater operations and would need to be considered in earnest. Surface-to-suit 2-way communications would be via the umbilical. Additionally, for ADSs operating in tandem, suit-to-suit communications could be via current through-water communication devices.

A vertical and horizontal *thruster package* would be added to the suit about mid-waist as part of the backpack structure. This would give the suit a greater mission range and allow the pilot more control for mid-water operations. The thrusters are typically operated via foot petals, but a joystick operation within the hand spheres could be further researched.

A *launching cage* is also proposed to reduce the inherent risks with launching the ADS from a moving platform in elevated sea states. At a minimal additional cost this will particularly protect the vulnerable limbs of the ADS from impact failure, during rough seas or in the event the launching system should fail, as evidenced by a recent offshore fatal accident in Oceaneering's WASP.

Another idea explored conceptually, but not specifically designed in this report is the ability to use *alternative tether systems* or no tether at all. A tether management system would allow the ADS to operate over an extended area without suffering the tether-induced drag normally associated with such operations. Additionally, a *non-tethered option* may have applications to the military, especially for clandestine operations.

Engineering Summary

Modeling each body component as individual pressure vessels yielded a nominal thickness of 0.3 in for all components (excluding the torso, which was 0.6 in thick). This resulted in a minimum Safety Factor of 2.31, which was deemed appropriate considering the imminent danger in the event of catastrophic failure of the pressure vessel. Most components had much greater Safety Factors, but thicknesses were kept consistent at 0.3 in for ease of manufacturing and joining. All dimensions are presented in Table A-1 of this report.

Buoyancy of the suit was determined and adjusted to be slightly negatively buoyant (1.0 lb.), with the use of syntactic foam bumpers, internal ballast and jettisonable external ballast.

To determine the amount and type of breathing gas needed for a standard and emergency mission, an accurate calculation of metabolic load (consumption of oxygen and the generation of carbon dioxide) is required. Because this suit will maintain standard pressure conditions, the focus of the calculations is on the amount of oxygen consumed and the carbon dioxide produced. Hypoxia (oxygen shortage) and hypercapnia (excess carbon dioxide) are avoided by replacing oxygen that is consumed and removing carbon dioxide that is produced. The amount of carbon dioxide in question can be calculated by multiplying the carbon dioxide generation rate by the density of carbon dioxide at standard conditions. This rate needs to be evaluated in terms of the length of the mission.

Next the amount of oxygen that will be consumed to produce the carbon is calculated. An internally pressurized canister provides the oxygen, while another canister provides passive scrubbing (removal) of carbon dioxide. Applying the volume of oxygen consumed, calculations for the size container to house the pressurized oxygen are then

undertaken. Next using the volume of carbon dioxide produced and the efficiency of lithium hydroxide at removing the carbon dioxide the size container needed for carbon dioxide removal is calculated. Finally, to ensure the integrity of our life support systems, external pressure calculations for the scrubber container and internal pressure calculations for the oxygen container are performed.

The main byproduct of the lithium hydroxide chemical reaction with carbon dioxide is the production of water. Secondarily, the reaction will produce heat. After careful calculation the heat produced is determined to be insignificant.

Heat transfer was minimized by the use of 1/4 inch of insulation on the interior of each component pressure vessel, this yielded an amount deemed suitable for full mission habitability (< 4kW) without any additional heating or cooling. Operators would simply dress appropriately, depending on the ambient environment.

Escape from the suit at depth would be impossible, therefore safety design was limited to the minimization of risk of life and the ability to recover the suit in event of emergency. Additions such as acoustic pingers, strobe beacons, and jettisonable ballast would assist in the recovery, and are standard fare on current ADSs. Safety procedures such as operating in pairs or limiting operations to water with bottom-depth not greater than the rating of the suit would additionally reduce the chance of a casualty. Per ABS rules, a 72-hour, in addition to normal mission time, emergency life support supply of gas is required and is standard equipment. Table C-1 is a comparison of this design to specific characteristics of existing or proposed atmospheric diving suits.

SUMMARY AND CONCLUSIONS

Summary

The atmospheric diving suit has evolved from a wooden barrel to an extremely complex and useful tool for underwater intervention. The joints have advanced from simple fabric seals to complicated yet fail-safe highly-mobile oil-supported rotary or segmented ball and socket joints. Its depth capability has increased steadily from 60 feet to close to 3000 feet. And, while the earliest ADSs were invented to salvage gold and other treasures from sunken ships, today's ADSs are more likely found supporting the offshore oil and gas industry's perpetual search for "black gold".

The atmospheric diving suit has some distinct advantages over other methods of intervention in the deep-sea environment. Most important, of which is the ability to put the human brain and eyes at the job-site where they are most effective, rather than separated by an umbilical and 1000's of feet of water. But, man is still at risk, a factor many companies consider when intervention planning.

Yet, the atmospheric diving suit is still evolving, albeit more slowly than in the past. Hardsuits has built a deeper suit, Oceaneering's WASP is being updated and will additionally add 200 feet of water-depth to it's capabilities, and the yet to be built EXOSUIT promises to be 'flexible' enough to allow the operator to swim freely.

Conclusions

The oil industry is poised to go deeper and deeper in search of oil. If the atmospheric diving suit is to continue to progress deeper, and keep pace, it will likely need the kind of industry support that was sought after to develop the JIM suit. The most restrictive limitation to going deeper, as has always been the case, is the ability to design a joint

that will maintain mobility while maintaining water-tightness. Though with the availability of alternative underwater intervention methods, especially those that can go deeper and without the risk of human life, no matter how small that risk may be, the ADS industry is unlikely to propel themselves deeper without a significant industry demand. Instead, ADS firms are more likely to continue to market themselves toward other interests, such as international Navies submarine rescue programs. Additionally, in the offshore oil and gas industry, they will presumably continue to extend their capabilities, within current depth limitations, by adding work packages that will allow them to perform a greater variety of tasks.

The advantages of the ADS are clear, but not always sufficient to warrant placing a human at the depths required to complete the job. Yet, the atmospheric diving suit seems firmly ingrained in the offshore oil and gas industry and will always be 'another tool in the toolbag', waiting for the opportunity when all factors point to it as the sensible choice for the task at hand. It is unlikely there will ever be another 100 year gap in the use of the atmospheric diving suit.

REFERENCES

Albaugh, E. Kurt, "1999 Gulf of Mexico survey of DSV, MSV, RSV vessels, and global ADS units", Offshore, 83-85, (Mar 1999).

Associated Press, "Study predicts increase in deepwater drilling", (May 2000).

Aylmer, A.R., "John Lethbridge: the first inventor of a diving engine, without communication of air", Historical Diver, No. 8, (1996).

Barton, R., "Armoured suit has 1000ft capability", Offshore Services, 18-21, (May 1973).

Beer, F.P., Johnston, E.R., Mechanics of Materials - 2nd Edition, McGraw-Hill, Inc., New York, (1992).

Burrow, Michael, "JIM", Oceans 2000: Third World Congress of Underwater Activities, 55-57, (1973).

Carter, Robert C., LT. "Evaluation of JIM: A One-Atmosphere Diving Suit". Navy Experimental Diving Unit Report 5-76. (Jul. 1976).

Cowan, Rex, "Cape Verde: the new Mecca for wreck-hunters", Diver, (Sep. 1999).

Croizeau, Isabelle. "Stranded At the Bottom of the Sea: Newtsuit to the Rescue". Discover Diving. (August 1999).

Davis, Sir Robert, Deep Diving and Submarine Operations: Fifth Edition, The Saint Catherine Press Ltd., (1951).

Earle, Dr. Sylvia, "Why Explore the Deep Sea", Marine Technology Society Journal, Vol. 33, No. 4, 80-82, (1999).

Earls, T.C., et al., "Operational Experience with Atmospheric diving suits", 11th Annual Offshore Technology Conference Proceedings, 1527 – 1531, (1979).

English, J.G., "JIM Atmospheric Diving System Arctic Operations", The Working Diver Symposium Proceedings, 225-231, (Mar 1978).

Fonda-Bonardi, B., Buckley, C., "Diving Suit from Space", Ocean Industry, (Sep 1967).

Fridge, David S., "Atmospheric suit designs challenge deep hyperbaric diving methods", Offshore, 140-141(May 1977).

Gorman, N., "Pluto gas flowline repaired at water depth of 2,150 ft", Offshore, Vol. 60, No. 6, (June 2000).

Harris, Gary L., Iron Suit: The History of the Atmospheric diving suit, Best Publishing Company, Arizona, (1985).

Hawley, G., Nuckols, M.L., Reader, G.T., Potter, I.J., Design Aspects of Underwater Intervention Systems, Kendall/ Hunt Publishing Company, (1996).

Hays, Kristen, "Fatality a reminder of diving's risks", Associated Press, (Jan 2000).

Huber, David, "On-bottom flowline repair in 1,000ft depths", Offshore, (Jun 1999).

Lethbridge, John, Letter of to the editor, The Gentleman's Magazine, (Sep.1749).

Loftas, Tony, "JIM: homo aquatico-metallicum", New Scientist, 621-623, (Jun 1973).

Matzen, Mary M., "Research Continues on JIM", Faceplate, Summer, 32-34, (1980).

Maberry, Steven, "Detailing the Physiology of Saturation Diving", Underwater Magazine, 106-107, (Jul 2000).

McCabe, Chuck and Charalambides, John, "Deepwater Spool Piece Repair", Underwater Magazine, 11-12, (Jul 2000).

McMichael, William H., "If it were ours…what would we do", Navy Times, 14-16, (Aug 2000).

Morrison, J. Scott, "A History of Atmospheric Diving Suits and the Development of the Highly Mobile Rotary Joint", Society of Automotive Engineers, Technical Paper 891687, (1989).

Nuckols, M.L., Tucker, W.C., Sarich, A.J., Life Support System Design, Simon & Schuster, MA., (1996).

Nuytten, Phil, "Inner Space and Outer Space – Some Observations on Overlap", Fourteenth Intersociety Conference on Environmental Systems, (Jul. 1984).

Nuytten, Phil, "NEWTSUB DeepWorker 2000 An Overview of Work-Class DOV", Proceedings of Underwater Intervention Conference, Houston, Texas, (1997).

Ocean Industry, "Two one-man submersibles on order", 59-60, (Oct. 1977).

Ocean Oil Weekly Report, Vol 34, No. 36, (Sep. 1999).

Pesce, G.L., La Navigation Sous-Marine, Vuibert & Nony, Paris, (1906)

Peterson, Kevin C., "Intervention Planning", Oil & Gas Journal, Vol. 58, No. 3, (Mar 1998).

Scott, David, Seventy Fathoms Deep, Faber & Faber, London, 1931).

Scott, David, The Egypt's Gold, Faber & Faber, London, (1932).

Randall, Dr. Robert E., Underwater and Mooring System Design, Texas A&M University, (2000).

Rieseberg, Harry E. Lieut., Mikalow, A.W., Fell's Guide to Sunken Treasure Ships of the World, Frederick Fell Inc, (1965).

Roebuck, John A., Anthropometric Methods: Designing to Fit the Human Body, Human Factors and Ergonomics Society, (1995).

Rules for Building and Classing Underwater Systems and Vehicles, American Bureau of Shipping, New York, (1979)

Sadorf, CDR Kurt R. "USN Deep Submergence Unit". Sea Technology. 45-48. (May 1999).

Taylor, C., "Jim, but not as we know it", Diver, 86-88, (Oct 1997).

Underwater Magazine, "Deepwater spending could double", 20-21, (Mar 2000).

Underwater Magazine, "How deep is deepwater?", p. 29, (Mar/Apr 2000).

Underwater Magazine, "Deepwater Production in the Gulf of Mexico Jumps Dramatically", 39-40, (Sep 2000).

van der Veen, Nick, "AUV Technology in Offshore Oil and Gas: Why? Will We?", Underwater Magazine, 62-63, (May2000).

Wharton, Ric, "Design and Utilization of the SPIDER", Ninth International Diving Symposium, (Feb. 1979).

Westwood, John W., "What the Future Holds for ROVs and AUVs", Underwater Magazine, 38-41, (May 2000).

APPENDICES

APPENDIX A

Spreadsheet of Atmospheric Diving Suit Calculations

Table A-1: Pressure Vessel Design Spreadsheet.

Design Properties				
Rated Depth	D	=	3000	fsw
Design Depth (+25%)	D	=	3750	fsw
Design Pressure	P	=	1684.7	psi
Temperature, seawater	T_{sw}	=	40	F
Temperature, internal	T_i	=	69	F

Insulation				
thickness	t_{ins}	=	0.25	in
thermal conductivity	k_{ins}	=	0.02	Btu/hr-ft-F

Convective Conductance	h_c	=	2	Btu/hr-ft²-F

Material Properties: Titanium Alloy				
Heat Transfer Coefficient	k	=	3.69	Btu/hr-ft-F
Specific Weight	γ	=	0.16	lb/in³
Poisson's Ratio	ν	=	0.34	
Yield Strength	σ_y	=	127.60	ksi
Modulus of Elasticity	E	=	16.50	$\times 10^6$ psi

Material Properties: Polycarbonate				
Heat Transfer Coefficient	k	=	0.12	Btu/hr-ft-F
Specific Weight	γ	=	0.04	lb/in³
Poisson's Ratio (assumed)	ν	=	0.30	
Yield Strength	σ_y	=	9.00	ksi
Modulus of Elasticity	E	=	0.35	$\times 10^6$ psi

Elements	Dimensions										Design Values		Weight/Buoyancy				Heat Transfer					
Cylindrical	L (in)	D (in)	t (in)	R (in)	R_o (in)	A (in²)	A_o (in²)	R_{eq} (in)	$t/2R_{eq}$	$L/2R_{eq}$	P_c (psi)	F.S.	V_{disp} (ft³)	V_H (ft³)	W (lb)	W_{net} (lb)	R_c	R_H	R_{ins}	R_{ci}	R(tot)	q(Btu/hr)
Forearm(1)	8	6	0.3	3	3.30	169.6	186.6	3.150	0.048	1.43	10680.22	6.45	0.178	0.147	8.604	-2.9	0.0004	0.0029	0.0027	0.0789	0.0930	349.39
Forearm(2)	8	6	0.3	3	3.30	169.6	186.6	3.150	0.048	1.43	10680.22	6.45	0.178	0.147	8.604	-2.9	0.0004	0.0029	0.0027	0.0789	0.0930	349.39
Upper Arm(1)	7	7	0.3	3.5	3.80	153.9	167.1	3.650	0.041	0.96	11530.84	6.84	0.164	0.156	7.754	-4.1	0.0006	0.0032	0.0030	0.0842	0.0910	318.77
Upper Arm(2)	7	7	0.3	3.5	3.80	153.9	167.1	3.650	0.041	0.96	11530.84	6.84	0.164	0.156	7.754	-4.1	0.0006	0.0032	0.0030	0.0842	0.0910	318.77
Upper Leg(1)	10	10	0.3	5	5.30	314.2	333.0	5.150	0.029	0.97	4732.17	2.81	0.511	0.455	15.629	-17.3	0.0002	0.0016	0.0015	0.0408	0.0442	656.81
Upper Leg(2)	10	10	0.3	5	5.30	314.2	333.0	5.150	0.029	0.97	4732.17	2.81	0.511	0.455	15.629	-17.3	0.0002	0.0016	0.0015	0.0408	0.0442	656.81
Lower Leg(1)	12	10	0.3	5	5.30	377.0	399.6	5.150	0.029	1.17	3887.82	2.31	0.612	0.545	18.755	-20.7	0.0002	0.0013	0.0013	0.0340	0.0369	760.17
Lower Leg(2)	12	10	0.3	5	5.30	377.0	399.6	5.150	0.029	1.17	3887.82	2.31	0.612	0.545	18.755	-20.7	0.0002	0.0013	0.0013	0.0340	0.0369	760.17
Foot (1)	14	6	0.3	3	3.30	263.9	280.3	3.150	0.048	2.22	6807.95	4.04	0.277	0.229	13.383	-4.5	0.0003	0.0019	0.0017	0.0495	0.0534	543.50
Foot (2)	14	6	0.3	3	3.30	263.9	280.3	3.150	0.048	2.22	6807.95	4.04	0.277	0.229	13.383	-4.5	0.0003	0.0019	0.0017	0.0495	0.0534	543.50
Torso	20	16	0.8	8	8.80	1407.4	1513.0	8.300	0.096	1.65	4533.03	2.69	3.766	3.256	141.057	-101.4	0.0001	0.0004	0.0003	0.0090	0.0098	2564.33

Spherical	D (in)	t (in)	R (in)	R_o (in)	A (in²)	A_o (in²)	t/R	C[1]	P_c[2] (psi)	P_y (psi)	F.S.	V_{disp} (ft³)	V_H (ft³)	W (lb)	W_{net} (lb)	R_c	R_H	R_{ins}	R_{ci}	R(tot)	q(Btu/hr)
Shoulder (1)	7	0.3	3.5	3.80	153.9	181.5	0.079	0.077	13154.8	55758.2	7.81	0.067	0.062	4.045	-0.2	0.0005	0.0032	0.0028	0.0942	0.0907	159.63
Shoulder (2)	7	0.3	3.5	3.80	153.9	181.5	0.079	0.077	13154.8	55758.2	7.81	0.067	0.062	4.045	-0.2	0.0005	0.0032	0.0028	0.0942	0.0907	159.63
Elbow (1)	7	0.3	3.5	3.80	153.9	181.5	0.079	0.077	13154.8	55758.2	7.81	0.067	0.062	4.045	-0.2	0.0005	0.0032	0.0028	0.0942	0.0907	159.63
Elbow (2)	7	0.3	3.5	3.80	153.9	181.5	0.079	0.077	13154.8	55758.2	7.81	0.067	0.062	4.045	-0.2	0.0005	0.0032	0.0028	0.0942	0.0907	159.63
Hand (1)	7	0.3	3.5	3.80	153.9	181.5	0.079	0.077	13154.8	55758.2	7.81	0.067	0.062	4.045	-0.2	0.0005	0.0032	0.0028	0.0942	0.0907	159.63
Hand (2)	7	0.3	3.5	3.80	153.9	181.5	0.079	0.077	13154.8	55758.2	7.81	0.067	0.062	4.045	-0.2	0.0005	0.0032	0.0028	0.0942	0.0907	159.63
Pelvis (1)	16	0.3	8	8.30	804.2	865.7	0.036	0.031	5303.8	8804.4	3.15	0.590	0.521	20.100	-24.5	0.0001	0.0006	0.0006	0.0150	0.0171	840.77
Knee (1)	10	0.3	5	5.30	314.2	353.0	0.057	0.053	9059.6	26445.9	5.38	0.160	0.152	8.051	-3.6	0.0002	0.0016	0.0014	0.0408	0.0441	329.09
Knee (2)	10	0.3	5	5.30	314.2	353.0	0.057	0.053	9059.6	26445.9	5.38	0.160	0.152	8.051	-3.6	0.0002	0.0016	0.0014	0.0408	0.0441	329.09
Hip (1)	10	0.3	5	5.30	314.2	353.0	0.057	0.053	9059.6	26445.9	5.38	0.160	0.152	8.051	-3.6	0.0002	0.0016	0.0014	0.0408	0.0441	329.09
Hip (2)	10	0.3	5	5.30	314.2	353.0	0.057	0.053	9059.6	26445.9	5.38	0.160	0.152	8.051	-3.6	0.0002	0.0016	0.0014	0.0408	0.0441	329.09
Ankle (1)	10	0.3	5	5.30	314.2	353.0	0.057	0.053	9059.6	26445.9	5.38	0.160	0.152	8.051	-3.6	0.0002	0.0016	0.0014	0.0408	0.0441	329.09
Ankle (2)	10	0.3	5	5.30	314.2	353.0	0.057	0.053	9059.6	26445.9	5.38	0.160	0.152	8.051	-3.6	0.0002	0.0016	0.0014	0.0408	0.0441	329.09
Head (1) Polycarbonate	16	2	8	10.00	804.2	1256.6	0.200	0.228	[illegible]	[illegible]	1.49	1.412	0.631	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0162	794.43

(1) Fig 5.3 Rules for Building and Classing Underwater Systems and Vehicles, American Bureau of Shipping, 1979

(2) Pressure allowable not to exceed the lower of P_c and P_y

TOTAL =	10.12268	8.78427	576.6	-161.9	12845.34 BTU/hr
			- Weight of Operator	175	3.766399 kW
			- CO2 Scrubbing Unit	10	
			- Other Internal Equipment	10	
			Internal Ballast	29	
			2 ft³ Syntactic Foam (AM-32)	-61	

+ Buoyancy = 1.8 lbs

Jettisonable External Ballast 2.5 lbs

APPENDIX B

Design Drawings of Atmospheric Diving Suit

Figure B-1: Atmospheric Diving Suit design drawing (Front View, Mesh)

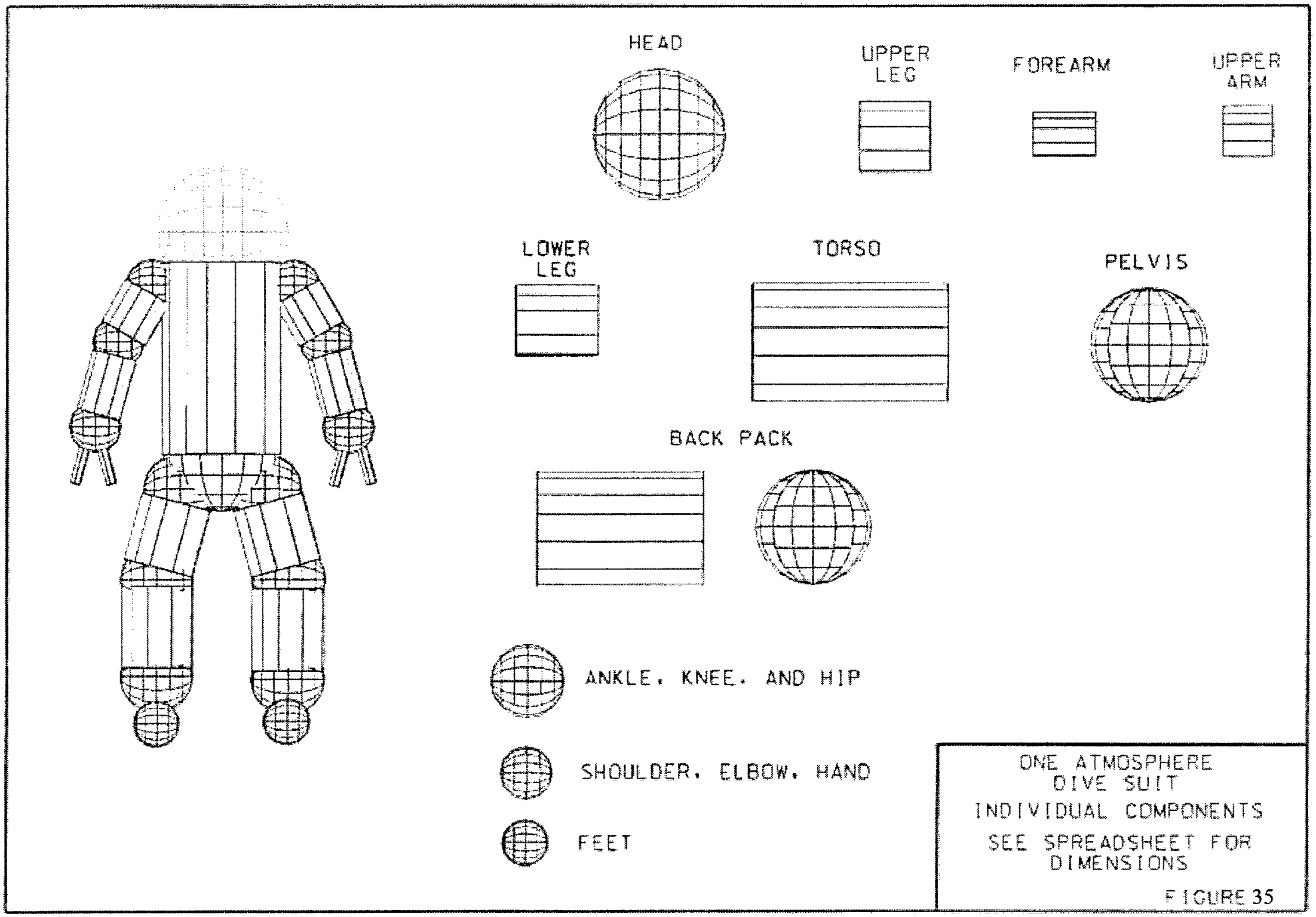


Figure B-2: Atmospheric Diving Suit design drawing (Front View, Solid)

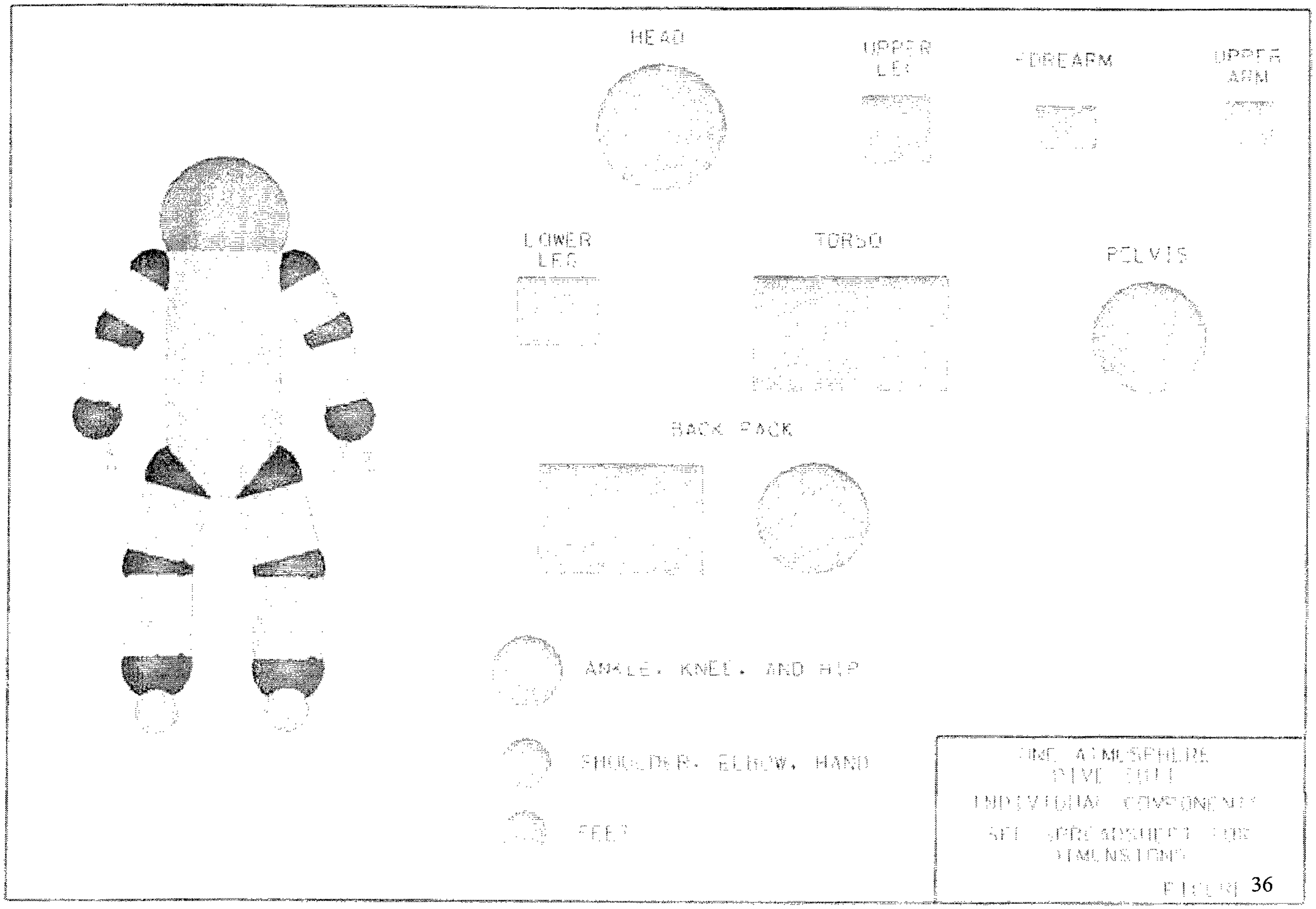


Figure B-3: Atmospheric Diving Suit design drawing (Side View, Mesh)

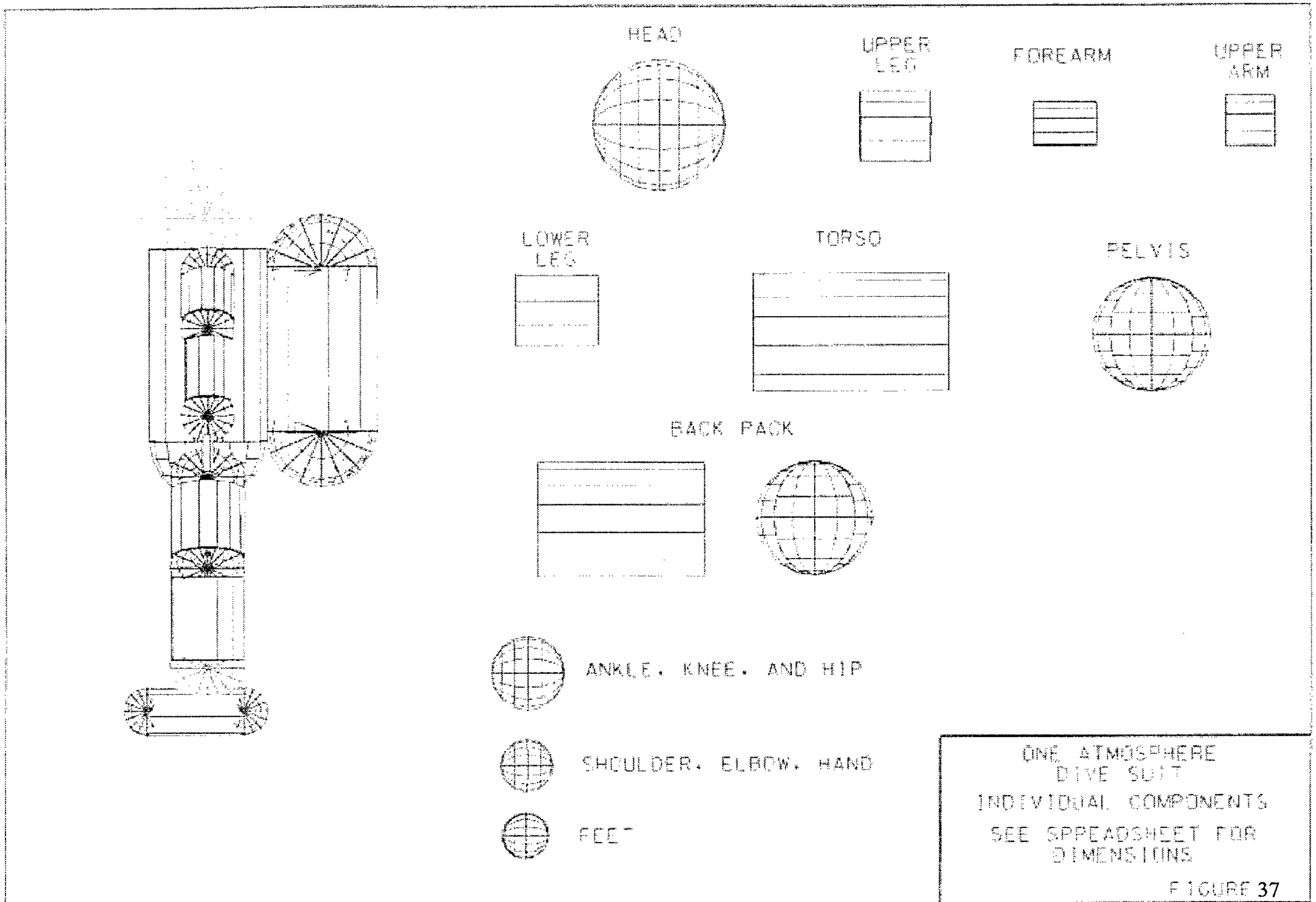
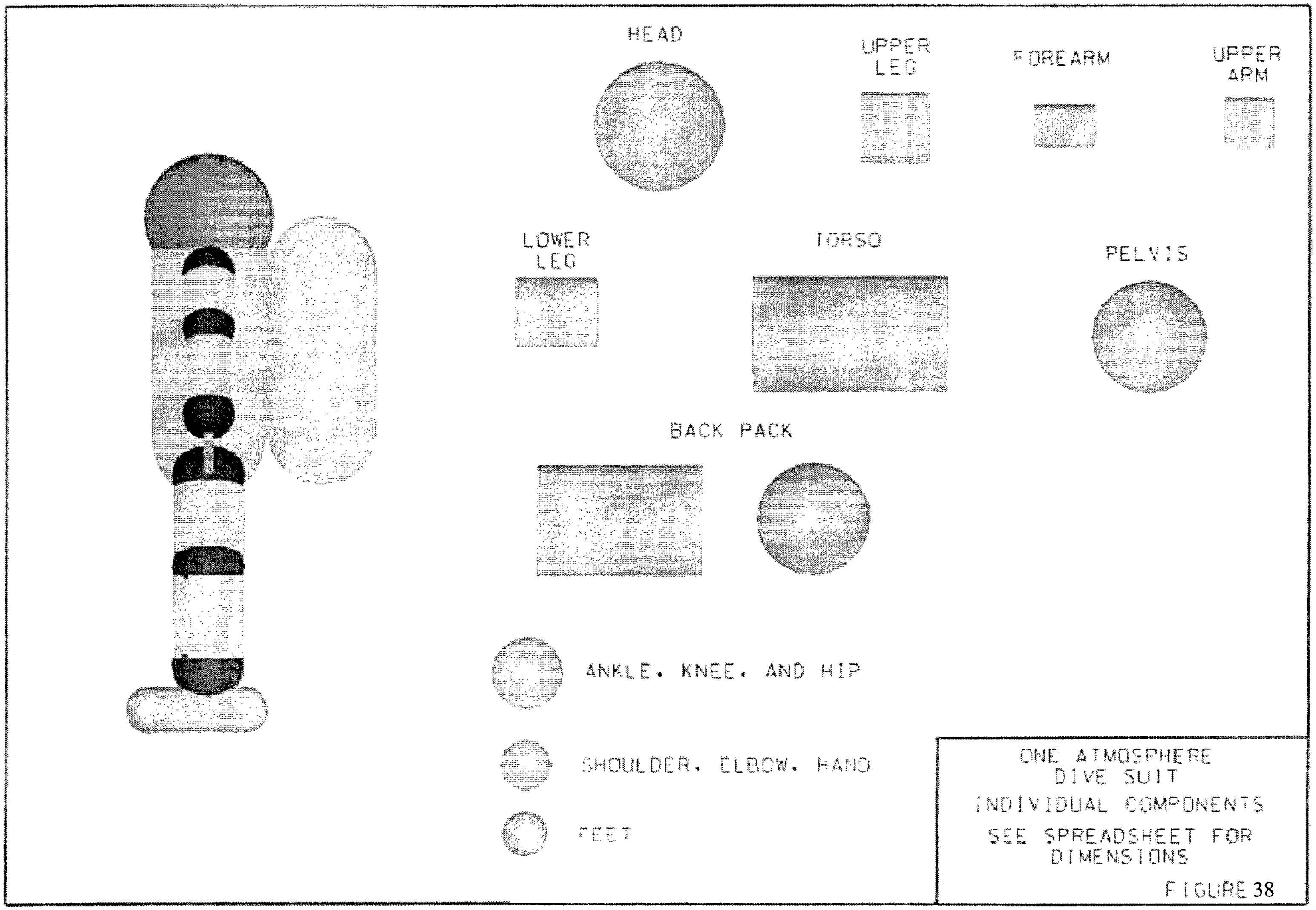


Figure B-4: Atmospheric Diving Suit design drawing (Side View, Solid)



APPENDIX C

Design Comparison to Existing Atmospheric Diving Suits

Table C-1: Design comparison to existing atmospheric diving suits.

SUITS [1]	OPERATIONAL PARAMETERS				CERTIFICATION	PRINCIPAL OVERALL DIMENSIONS					MATERIAL	
							WIDTH		WEIGHT			
	DEPTH RATING	MISSION LIFE SUPPORT	EMERGENCY LIFE SUPPORT	BREATHING GAS	CERTIFICATION	OVERALL HEIGHT [2]	FRONT	SIDE	IN AIR	IN WATER	HULL	INSULATION
	FSW (m)	HRS	HRS			IN(cm)	IN(cm)	IN(cm)	LBS(kg)	LBS(kg)		
PROPOSED ATMOSPHERIC DIVING SUIT DESIGN												
ADS 3000	3000 (900)	12	72	O_2	ABS	80[3](203)	40[3](102)	30[3](76.2)	575[4](261)	2.5(1.1)	Titanium	•
OCEANEERING INTERNATIONAL, INC.												
WASP 2A	2300 (700)	12	72	O_2	Lloyd's	84(213)	42(107)	32(81.3)	2,200(998)	+/- 20(9)	GRP	
STOLT OFFSHORE, INC. (HARDSUITS INTERNATIONAL)												
HARDSUIT™1000	1000 (300)	12	48	O_2	Lloyd's	81.2(206)	40(102)	30(76.2)	1,030(467)	4(1.8)	Cast Al	
HARDSUIT™1200	1200 (365)	12	54	O_2	Lloyd's	81.2(206)	40(102)	30(76.2)	1,030(467)	4(1.8)	Cast Al	
HARDSUIT™2000	2000 (600)	12	48	O_2	U.S. Navy	93(236)	48(122)	31(78.7)	1,160(526)	4(1.8)	Forged Al	
HARDSUIT™2500 [5]	2500 (760)	12	48	O_2	Under Construction	93(236)	48(122)	31(78.7)	1,160(526)	4(1.8)	Forged Al	
SILVERCREST SUBMARINES												
SPIDER ADS	2000 (600)	12	72	O_2	In Recertification	88.3(224)	46(117)		2,200(998)	+/- 20(9)	GRP	
NUYTCO RESEARCH LTD.												
EXOSUIT [6]	300 (100)		48	O_2	Pre-Production	76(193)	30(76)		160(73)		Composite Fiber	

Definitions & Notes:

FSW - Feet of Sea Water

GRP - Glass Reinforced Plastic

1 Information sources: Oceaneering, Stolt Offshore, Silvercrest Submarines, Nuytco Research Ltd, U.S. Navy.

2 HARDSUIT overall height can be adjusted by extension rings in the legs to accommodate pilot sizing.

3 Dimensions are approximate and do not account for joint sizing or external equipment.

4 Does not include any peripheral equipment such as cameras, sonar, lights, etc.

5 The commercially available version of the HARDSUIT 2000 will be certified to 2500 feet (760 meters).

6 The EXOSUIT is in pre-production stage/beta test. Specifications are preliminary and subject to change.

VITA

Michael "Mike" Thornton is a Naval Civil Engineer Corps Officer in the Ocean Facilities Program with over eleven years of combined enlisted and commissioned active duty time. His most recent tour of duty was with Naval Mobile Construction Battalion Five where his jobs included: Chemical Biological Radiological Officer, Company Commander, Training Officer and Detail Officer-in-Charge in Guantanamo Bay, Cuba. His next assignment is the Director of the Diving Operations Division at Naval Facilities Engineering Service Center in Port Hueneme, California. He has a Bachelor of Mechanical Engineering from Auburn University and is currently completing a Master of Engineering in Ocean Engineering at Texas A&M University.